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Technical Summary Report 1 | *Covering the Period 1 June to 1 December 1963*

THE INVESTIGATION OF THE APPLICATION OF MODERN SPARK GAP TECHNIQUES TO HIGH-POWER TRANSMITTER DESIGN

Prepared for:

OFFICE OF NAVAL RESEARCH
WASHINGTON, D.C.

AND

ADVANCED RESEARCH PROJECTS AGENCY
WASHINGTON, D.C.

CONTRACT Nonr-4178(00)
ARPA ORDER 463

By: *L. T. Dolphin, Jr.* *A. F. Wickersham, Jr.* *F. E. Firth*

STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

*SRI

January 1964

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SRI Project No. 4548

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ABSTRACT

A novel scheme for generating large amounts of RF power at HF and VHF has been proposed by scientists working at the University of New England in Armidale, New South Wales, Australia. This scheme, adapted from the Marx impulse generator, combines transmitter and antenna into a single unit. Capacitors, charged in parallel and discharged in series, tune with the inductance of their mounting ring to form a resonant circuit at the desired operating frequency. Radiation resistance is the principal dissipative element in the circuit, leading to high efficiency. The capacitors are charged to voltages from 10 to 200 kv, leading to peak powers which conceivably could be as high as 10^4 to 10^8 Mw. Pulse widths achievable with the basic structure range from a fraction of a microsecond to a few microseconds.

Improvements to the original device have been suggested in order to increase the pulse length and permit CW operation and modulation.

The theory, problem areas, and applications of all aspects of this transmitter scheme are being studied at SRI. Highspeed plasma switches to permit long-pulse and CW operation are being exhaustively studied, and scale models of rings are under study as well.

Results to date with the basic ring structure are encouraging: however, there appear to be difficulties in developing a suitable plasma switch for CW operation.

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I INTRODUCTION

The spark ring transmitter was conceived by K. Landecker of the University of New England, Armidale, New South Wales, Australia, several years ago and recently reported by Dr. Landecker and associates in the Australian Journal of Physics.[1*] SRI contact with Dr. Landecker was established through Prof. O. G. Villard, Jr. of Stanford University in 1960. Prof. Villard foresaw the possibilities of such a transmitter in important applications in communications and upper atmospheric research. Subsequent correspondence between SRI and Dr. Landecker established the soundness of the theory and importance of investigating these novel spark-gap techniques for generating large amounts of RF power. The program reported herein is an outgrowth of Dr. Landecker's ideas, and at present, complements his continuing studies.

The principle of operation of the ring device is straightforward; however, there are many engineering problems that could preclude constructing suitable operating transmitters. It has been important to make thorough engineering evaluations in order to keep the research oriented toward practical and physically realizable transmitters, particularly when modifications and improvements have been discussed.

High-speed plasma switch devices would make it possible to extend the operation of the basic transmitter device to long-pulse and CW operation, including modulation. Considerable effort has been made, therefore, in exploring and testing various possibilities for plasma switches.

Replacement of the individual spark gaps with a single gap, connected to the ring with half-wave transmission lines, also has been investigated.

The possibilities of the ring transmitter continue to be very promising, although satisfactory achievement of the long-pulse and CW operation is not presently in sight.

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*References are listed at the end of the report.

II THEORY

A. Basic Principles

In its simplest configuration, the ring spark transmitter is nothing more than a tuned magnetic dipole. Capacitors are arranged around the circumference of a ring and connected in series through spark gaps. The inductance of the ring and the series capacitance of the capacitors are resonant at the operating frequency of the device. The quality factor of the ring (ratio of energy stored to energy dissipated per cycle) is determined principally by ring reactance and radiation resistance.

Figure 1 is a sketch of the ring transmitter in its simplest configuration. High voltage is supplied to each capacitor through series resistances or chokes. Spark gaps are in series with each capacitor, and connect the capacitors in series when the ring is in operation. The inductances, illustrated schematically, are distributed continuously around the ring, and the total inductance is dependent on the ring diameter and the radius of the current path.

The inductance of a circular loop whose radius is a, and with an average cross-sectional radius b, is

$$L \approx \mu_0 a \quad \ln \frac{8a}{b} - 1.75 \qquad \text{henries}$$

The equations is plotted in Fig. 2 for various ring radii and for three ratios of b/a.

The radiation resistance, R', of a circular loop with diameter comparable to wavelength is given by

$$R' = \frac{1}{2} \pi \mu_0 ck \int_0^{2k} J_2(x)\,dx \qquad \text{ohms} \quad ,$$

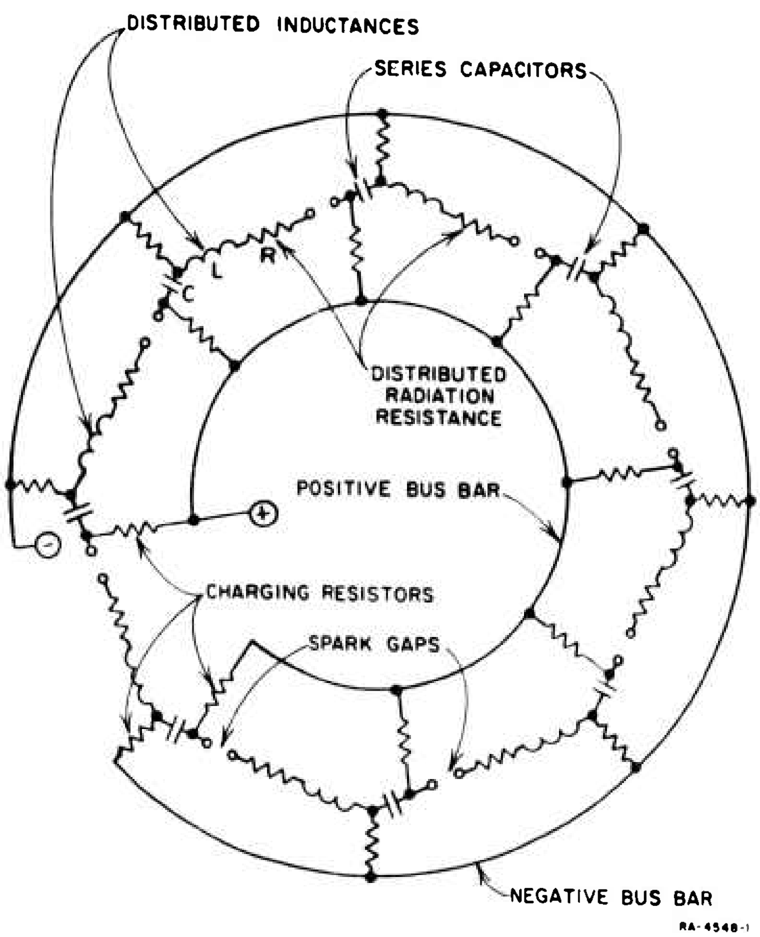


FIG. 1 BASIC RING SPARK TRANSMITTER

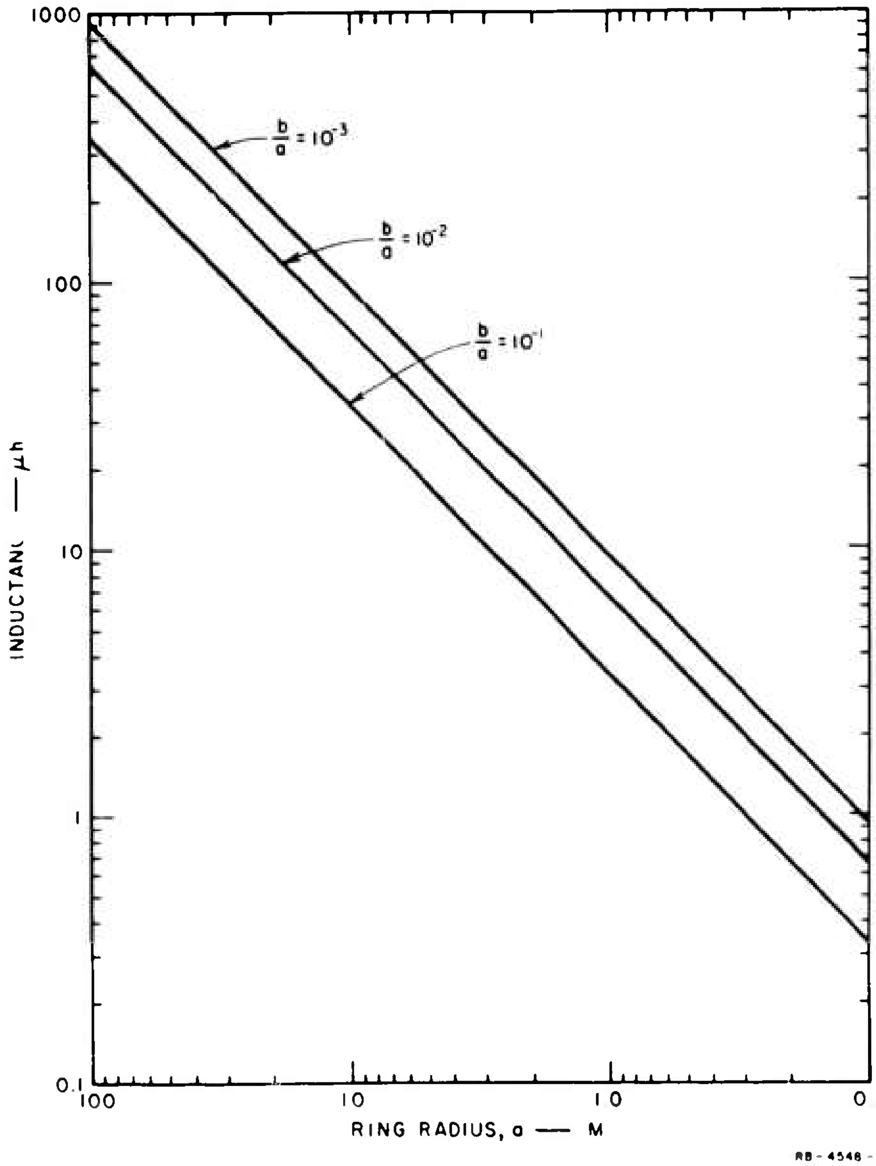


FIG. 2 RING INDUCTANCE AS A FUNCTION OF RADIUS

where μ_0 and C are the permeability and velocity of propagation in free space, k is equal to the ratio of ring radius to wavelength ($2\pi a/\lambda$), and $J_2(x)$ is a Bessel function of first kind and second order. This result may be expanded in the series for computation:

$$R^* = 20\pi^2 k^4 \left(1 - \frac{k^2}{5} + \frac{k^4}{58} - \frac{k^6}{1080} + \ldots\right)$$

Figure 3 shows the radiation resistance, computed from the above services, as a function of the ratio of ring diameter to wavelength. For convenience in the discussion, the curve of Fig. 3 has been multiplied by various quality, or "Q", factors and redrawn in Fig. 4. Figure 5 is a reactance chart for determining net capacitance required to tune a ring to resonance at a desired frequency. The achievable quality of a ring transmitter is limited by the choice of pulse length and bandwidth, as discussed below.

Landecker[1] has pointed out that the circular loop antenna will retain the character of a magnetic dipole for diameters as large as a wavelength. In practice, the ratio of ring diameter to wavelength is usually restricted to the range $0.18 \leq 2a/\lambda \leq 1.2$.

For $2a/\lambda > 1.2$ there will no longer be a single lobe to the antenna pattern; however, in some applications it may be desirable to exceed such a limit.

B. Energy Storage and Power Output

Each capacitor stores $1/2\ CV^2$ joules of energy, where C is the capacitance in farads, and V the potential in volts. If a ring contains N capacitors in series, a total of $1/2\ NCV^2$ joules of energy will be stored in the ring. As soon as the spark gaps discharge, an oscillatory current will flow in the ring. This current will be damped in time: exponentially if the radiation resistance is the controlling resistance, linearly if spark losses are high.[2] The energy in the circuit can be expressed as

$$\frac{1}{2} NCV^2 = \int_0^{\infty} I_0^2 R \exp - \frac{\omega t}{2Q} \sin^2 \omega t dt \quad ,$$

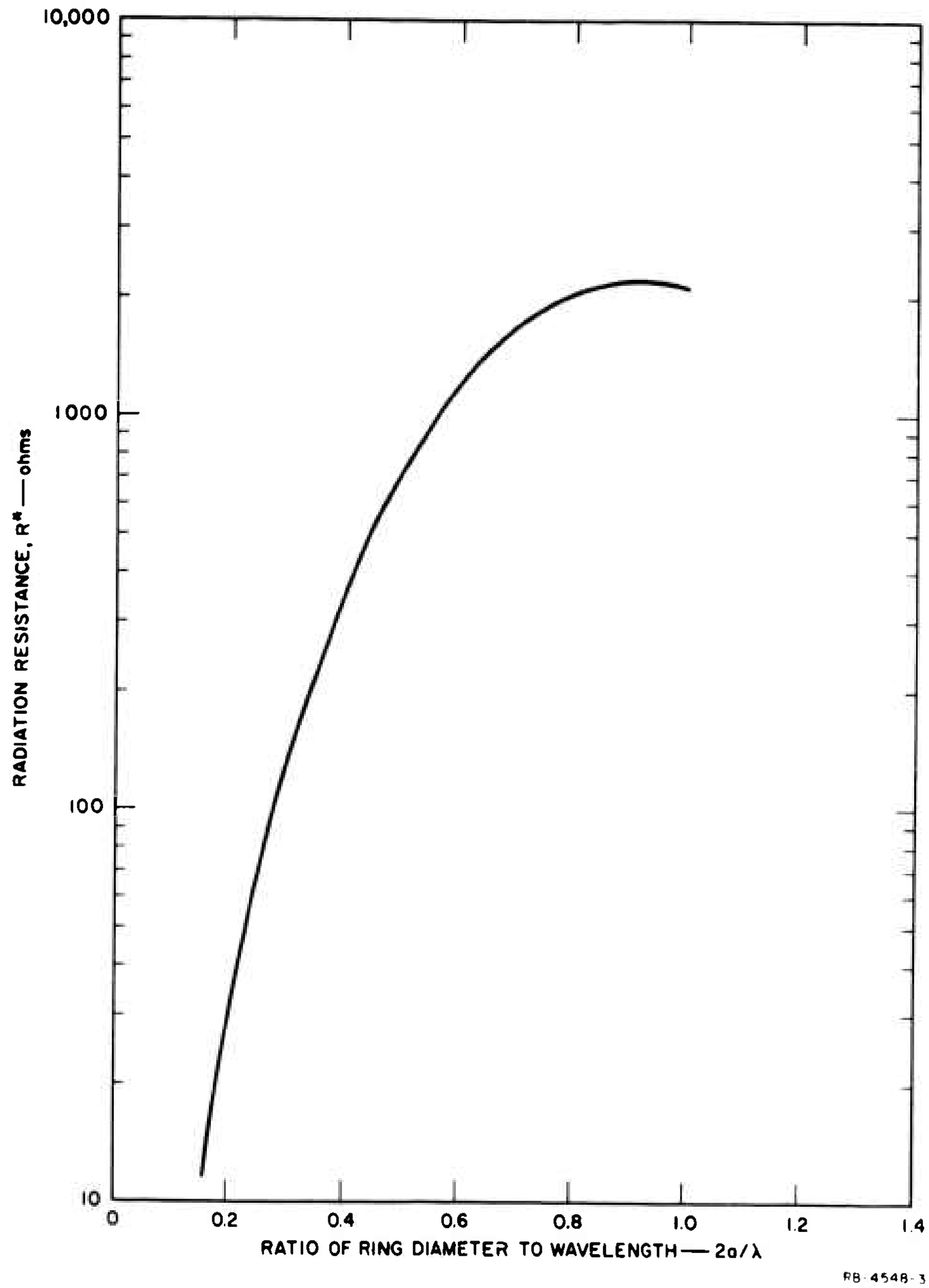


FIG. 3 RADIATION RESISTANCE OF CIRCULAR-LOOP ANTENNAS

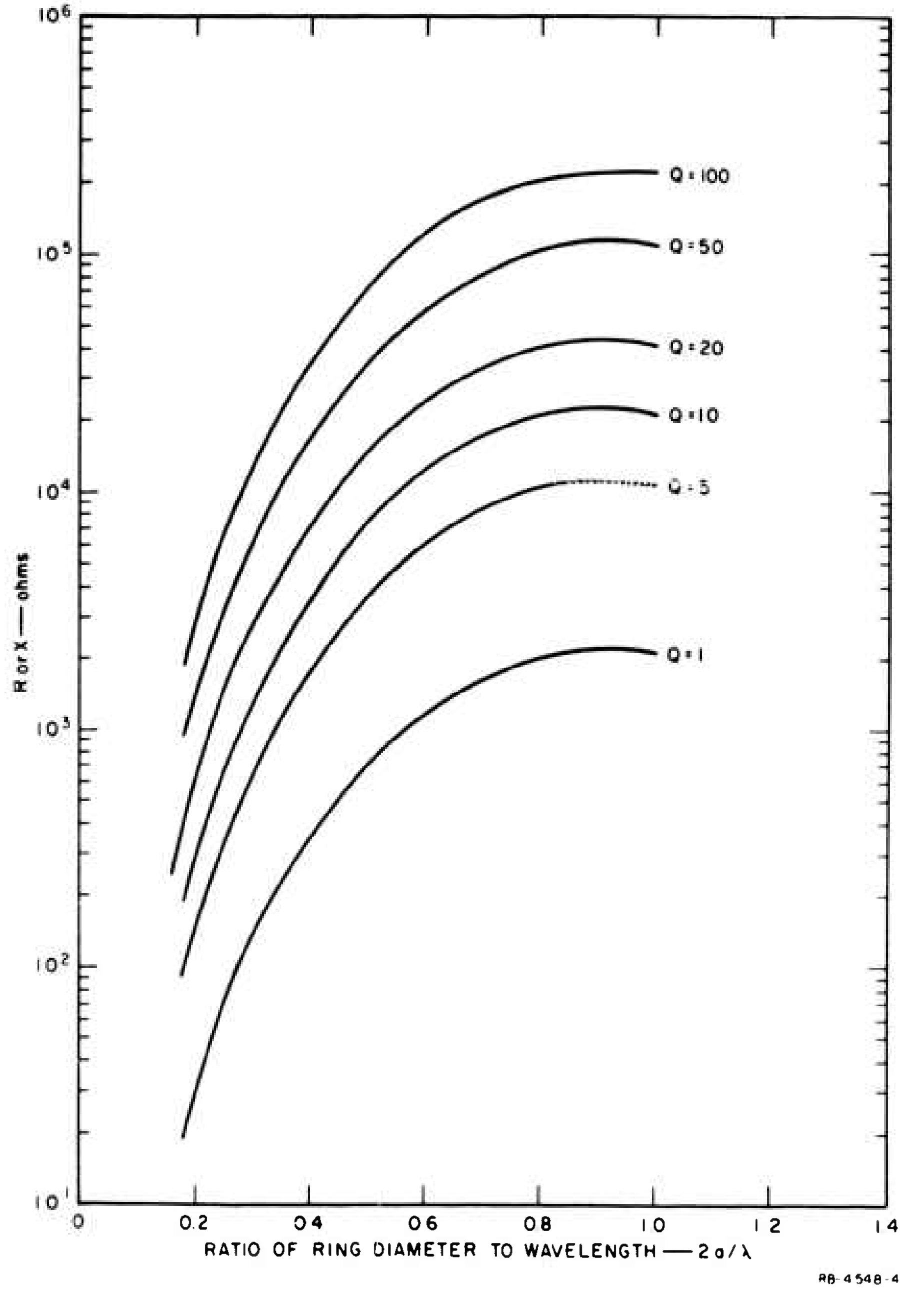


FIG. 4 RING REACTANCE AS A FUNCTION OF DIAMETER

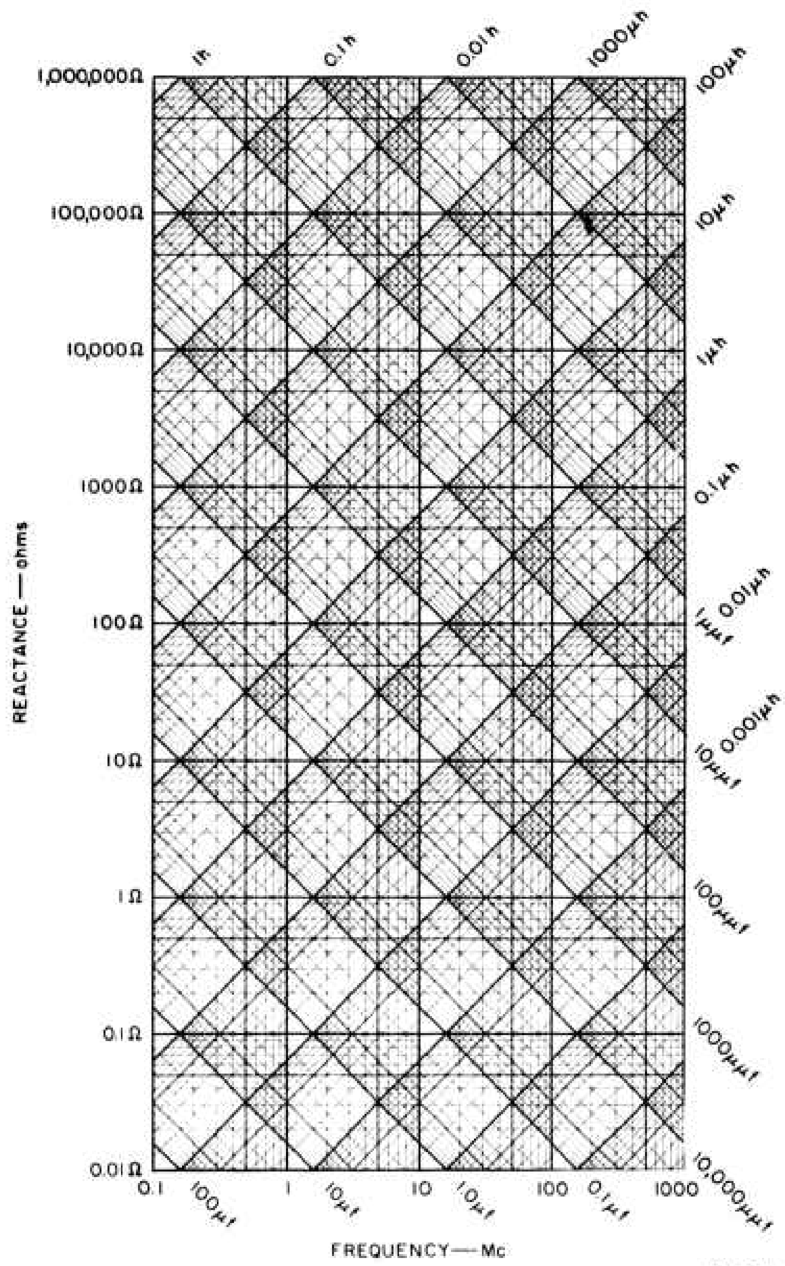


FIG. 5 REACTANCE CHART FOR SPARK TRANSMITTERS

where $\omega = (N/LC - R^2/4L^2)^{1/2} \approx (N/LC)^{1/2}$ and $I_0 = NV/L\omega$. The basic ring transmitter is fully equivalent to a series LCR circuit where R is the sum of radiation resistance and spark-gap losses, L the inductance of the ring, and $C = C_i/N$ is the net capacitance of all the capacitors in series.

The spark losses are normally small, so that the pulse decays exponentially in time, the decrement being a function of the circuit Q, which for a series circuit is the ratio of the reactance of either the inductance or capacitance (at resonance) to the total resistances. Q values from 10 to 50 are typical for a ring. The average power output of the transmitter during the first half of the first radio frequency cycle is $[(1/2)NCV^2](\omega Q)$. The instantaneous peak in the first half of the cycle is twice this value. It can easily be shown that the transmitted pulse has decayed to 10-percent power in 1.5/4 Q cycles, or $\tau = 2.5\ Q/\omega$ seconds. Figure 6 is a plot of pulse length to the 10-percent power level for various values of Q, and various frequencies. The pulse length to the 1-percent power point is twice as long, and these curves refer only to the basic ring device without any secondary, parasitic elements, or additional means of energy storage.

In designing ring spark transmitters, several iterative estimates of ring parameters are made in order to arrive at a good compromise between energy storage, operating frequency, and quality, or pulse length. A large number of capacitors should be used, limited only by the available space around the ring, in order to obtain maximum power. High operating Q increases the pulse length; secondary circuits may also extend the pulse.

The simplest spark gap consists of two spaced electrodes, unenclosed and unquenched. Spark losses are usually small compared to the radiation resistance, unless the ring is small compared to a wavelength. An electrostatic shield can be extended over the spark gaps to prevent noise radiation at high frequencies; in fact, the whole ring can be enclosed in a metal torus. No potential difference exists across any two points of such a shield, so that radiating properties are preserved. Such a torus could be pressurized or evacuated to permit operation at extremely high voltages.

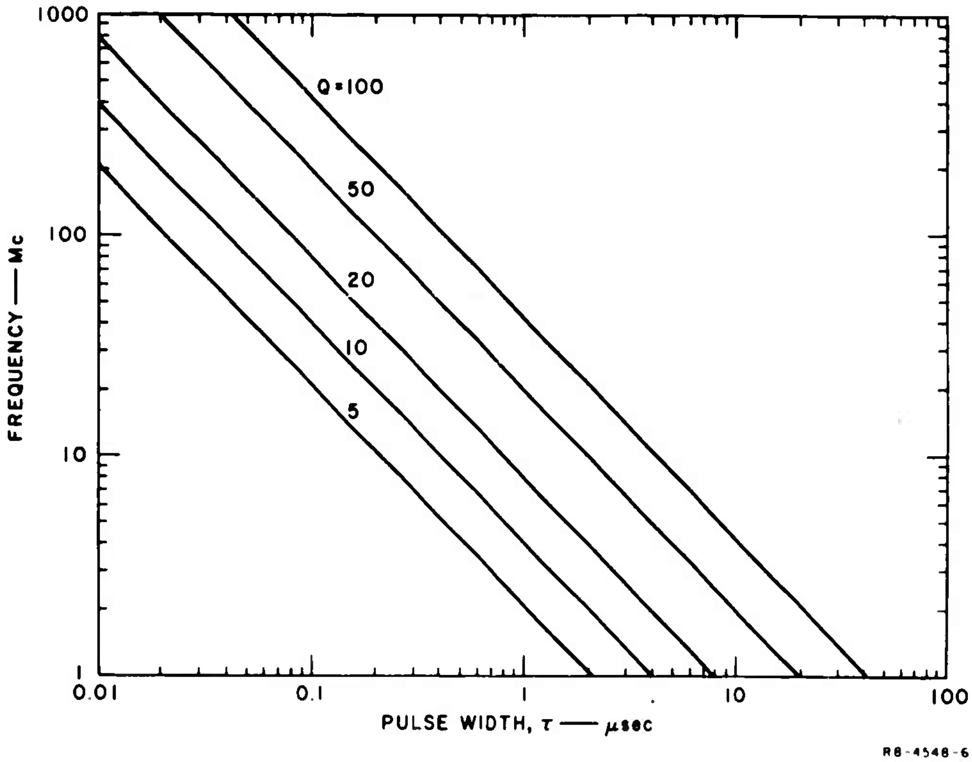


FIG. 6 RING TRANSMITTER: PULSE WIDTHS TO 10-PERCENT POWER LEVEL

C. Synchronization of Multiple Spark Gaps

To appreciate the importance of synchronization, consider for simplicity a ring of four identical capacitors charged in parallel to identical voltages and subsequently to be connected to series and discharged (Fig. 7).

Before the first spark gap is discharged, an electric field extends outside all of the capacitors as well as inside. Since the system is in static equilibrium, there is no magnetic field, only a conservative electric field. Thus no work will be done on carrying a test charge around any closed path in the system. By considering a test charge to be carried around the ring and returned to its starting point, we conclude that the potential difference between the outside of the capacitors is equal and opposite to the potential difference across a capacitor.

When the first spark gap is discharged, the external field between the adjacent capacitors must disappear and a new equilibrium be established, as shown in Fig. 7. By repeating the test-charge argument, we find now that the three remaining external potentials must be equal and opposite to the four internal potentials or $V_{ex} = 4/3\ V\ in$. Thus, just before the last spark gap discharges, there must be a potential of $nV_{in} = 4V_{in}$ across the last gap, where n is the number of capacitors in the ring. The energy stored across the last spark gap [$1/2\ C_{ij}\ (nV_{in})^2$, where C_{ij} is the intercapacitor capacitance, and V_{in} the potential across the capacitors], is less than the potential across a capacitor before the n-1 spark gaps were discharged. The energy stored internally by the capacitors is $n(1/2\ CV_{in})^2$; thus, even if the internal capacitance is much larger than the capacitance between condensers, there may be considerable energy stored outside the capacitors. For example, since the ratio of external to internally stored energy is nC_{ij}/C, the total energy will be equally divided, internally and externally, if $C = nC_{ij}$, and under such circumstance the operating efficiency will not exceed 50 percent.

When the last spark gap is fired, the externally stored energy will be discharged at a frequency of $\sqrt{C/C_{ij}}$ times the operating frequency.

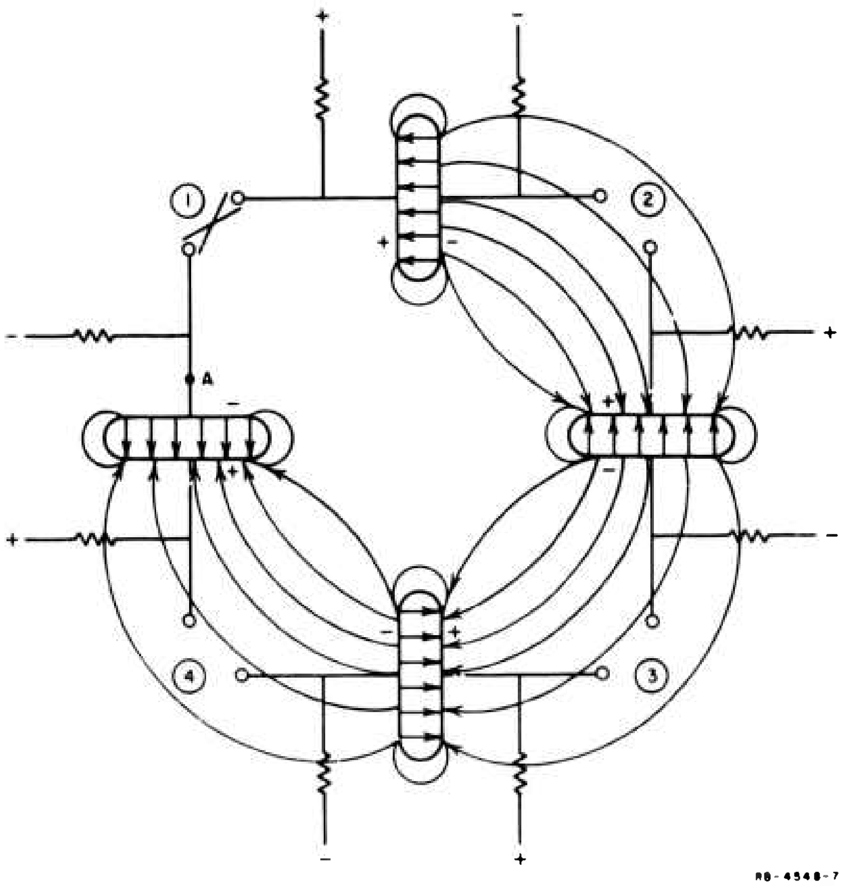


FIG. 7 ELECTRIC FIELDS IN A BASIC RING TRANSMITTER

This external discharge will add or interfere with the desired discharge of internally stored energy, and the resultant wave pattern will resemble that shown in Fig. 8.

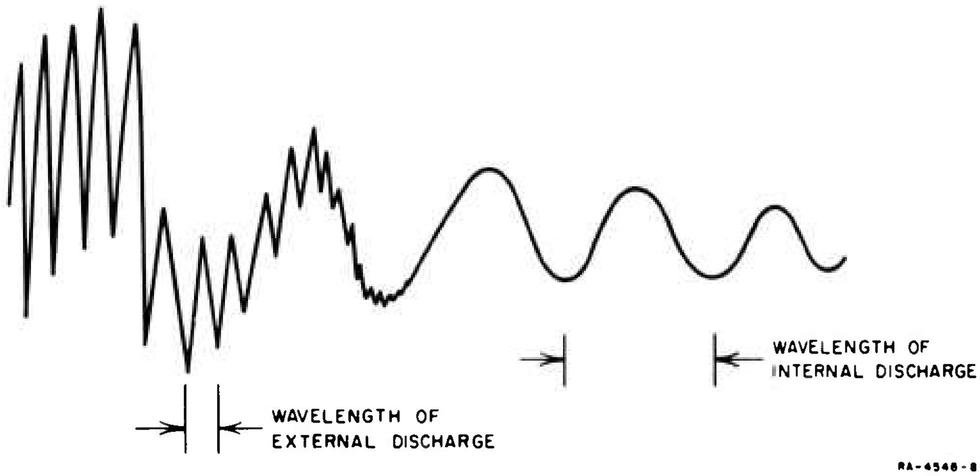


FIG. 8 DETAILED WAVE FORM OF DISCHARGE

In the random firing of n spark gaps, regions of high external potentials may be isolated in various sections of the ring; thus, when the last gap or gaps are discharged, one or several higher-frequency oscillations may be initiated. In such cases, the initial portion of the transmitted pulse would show an irregular interference, of random character, eventually decaying and leaving only the pulse derived from the internal discharge. Under such conditions it may happen that some spark gaps do not discharge during operation of the transmitter. We propose to study such cases by photographing the spark gaps during operation of the ring transmitter now being constructed.

In a spark transmitter with a multiplicity of gaps, a considerable loss of energy may occur owing to the finite resistance of the discharges in the gaps. In a recent discussion with Dr. Wulf Kunkel at Lawrence Radiation Laboratories, we learned that Philip Davenport at Culham Laboratory, Harwell, England has made a significant reduction in gap losses by using a "stay-alive" circuit. The stay-alive circuit is a means of maintaining a low-voltage, direct-current discharge across a gap during the time of operation. This prevents current reversals in the gap, such reversals apparently being major sources of energy loss.

The problem of spark losses will be studied in detail in the near future.

D. Central Spark Gap

The first major improvement suggested by the Australians was the replacement of the N individual spark gaps between each capacitor with a single spark gap connected to the ring by N transmission lines, each a half-wavelength long (Fig. 9). The impedance at the end of a

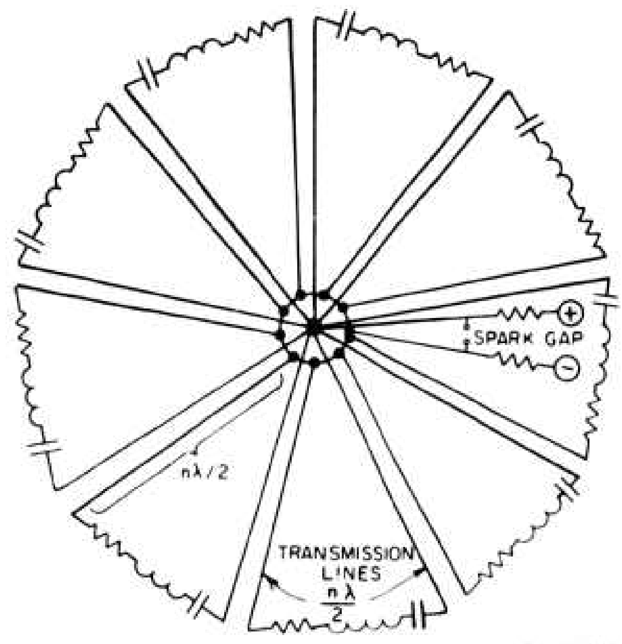


FIG. 9 IMPROVED RING TRANSMITTER

half-wavelength transmission line, short-circuited at the other end, is very low: it would be zero except for the losses in the line. Thus, at the desired operating frequency, the transmission lines short-circuited by a central gap should be equivalent to the old arrangement of N gaps.

There is no question of simultaneity of gap firing when there is only one gap, if the transmission lines are exactly equal in electrical length, and since the single gap is located at a current point it now has a lower resistance due to more current flowing through it.

A serious problem in using transmission lines to connect the ring to a central spark gap is the transmission-line losses. The ring transmitter is a low-impedance device, with typically only 20 to 100 ohms of total radiation resistance. If there are 50 capacitors in the ring, and 50 transmission lines, the transmission lines will lead to substantial losses by adding series resistance into the ring. If each of 50 transmission lines inserts only 1 ohm of series loss in the ring, the total of 50 ohms of loss could easily be comparable with, or greater than, the total radiation resistance of the ring. The transmission lines may operate at high standing wave ratios (VSWR), and this would compound the losses. Ideally, the interconnecting lines should be strip transmission lines with characteristic impedances of 5 to 15 ohms, or less.

For a transmission line of characteristic impedance R, cut to exactly a half wavelength, and operating at a high VSWR (>10), the resistance, R_1, at the open end, with the far end short-circuited by a small resistance, R_2 (the spark gap resistance), is given by[3]

$$R_1 = R_2 + \frac{R_0 \gamma_1 \lambda}{530} \quad \text{ohms} \quad ,$$

where γ_1 is the transmission line attenuation in db/100 ft. Figures 10 through 13 present loss data for various commercial 50-ohm transmission line types. As an example, the above formula shows that a half-wavelength of RG-17/U transmission line at 30 Mc will introduce 0.5 ohm of loss, even if the spark losses are zero ($R_2 = 0$). With 50 transmission lines, there would be a total of 25 ohms in the ring owing to transmission lines alone. To keep line losses small compared to radiated power, it would be necessary either to choose a high value of radiation resistance, or to use a transmission line of very low characteristic impedance.

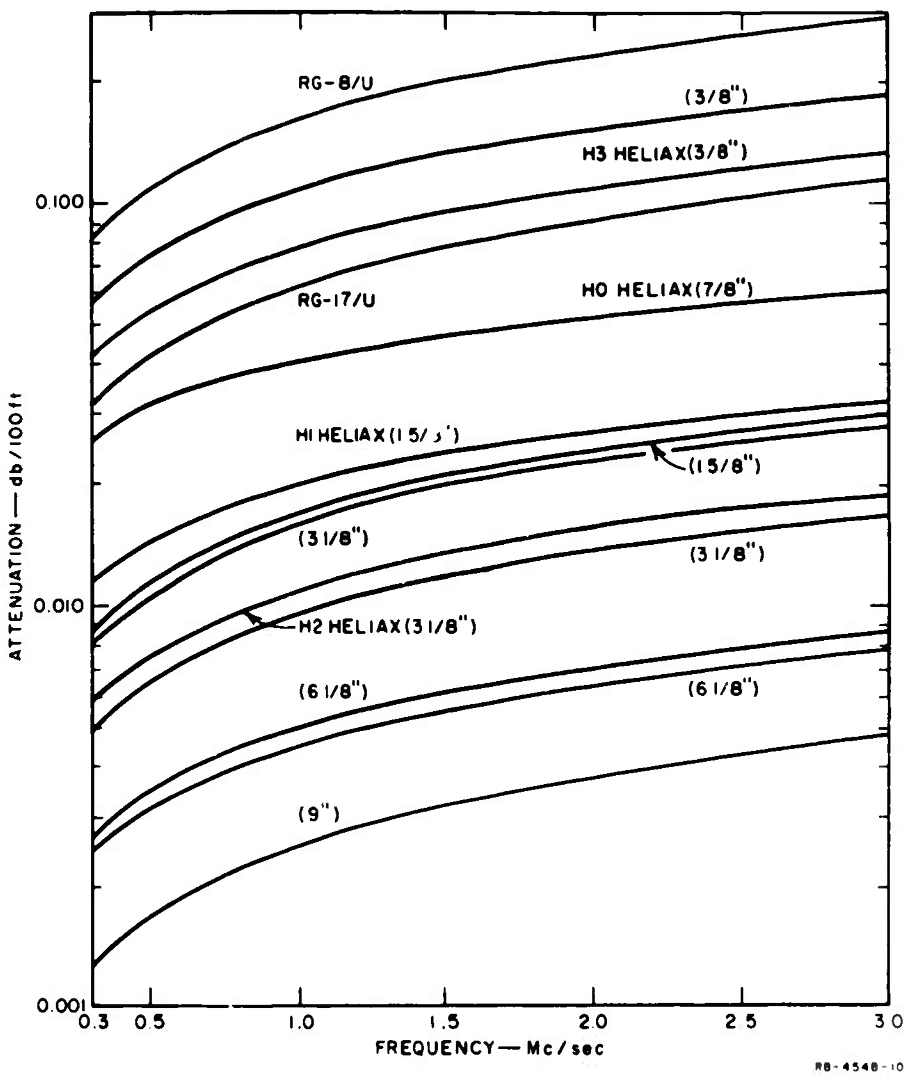


FIG. 10 TRANSMISSION-LINE ATTENUATION, 0.3 TO 30 Mc

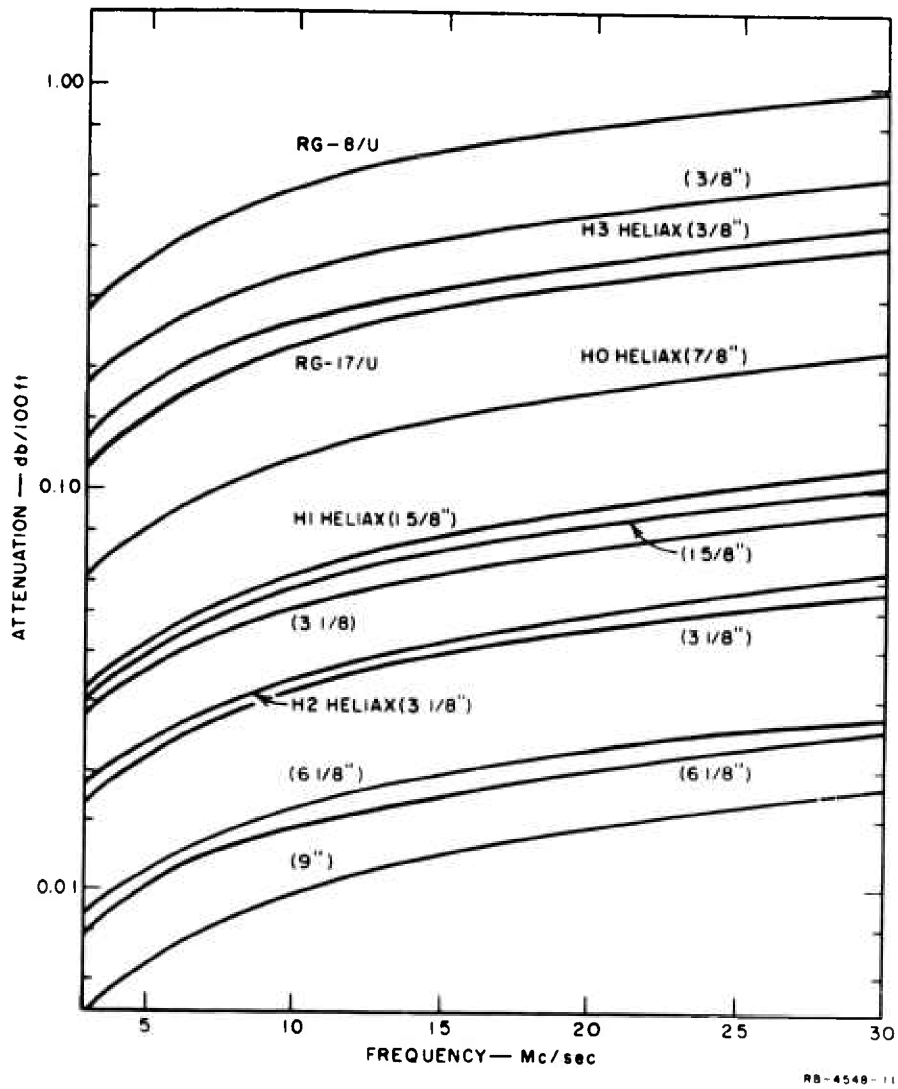


FIG. 11 TRANSMISSION-LINE ATTENUATION, 3 TO 30 Mc

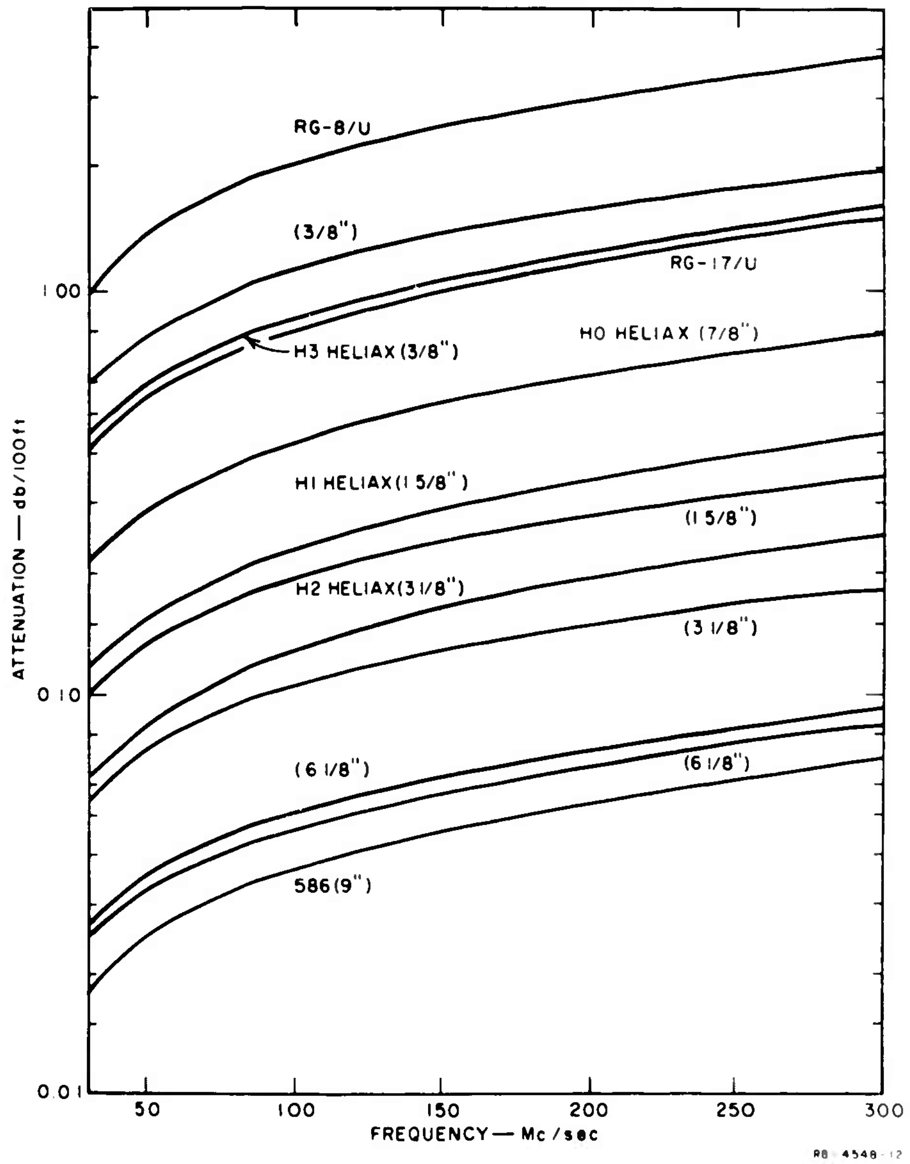


FIG. 12 TRANSMISSION-LINE ATTENUATION, 30 TO 300 Mc

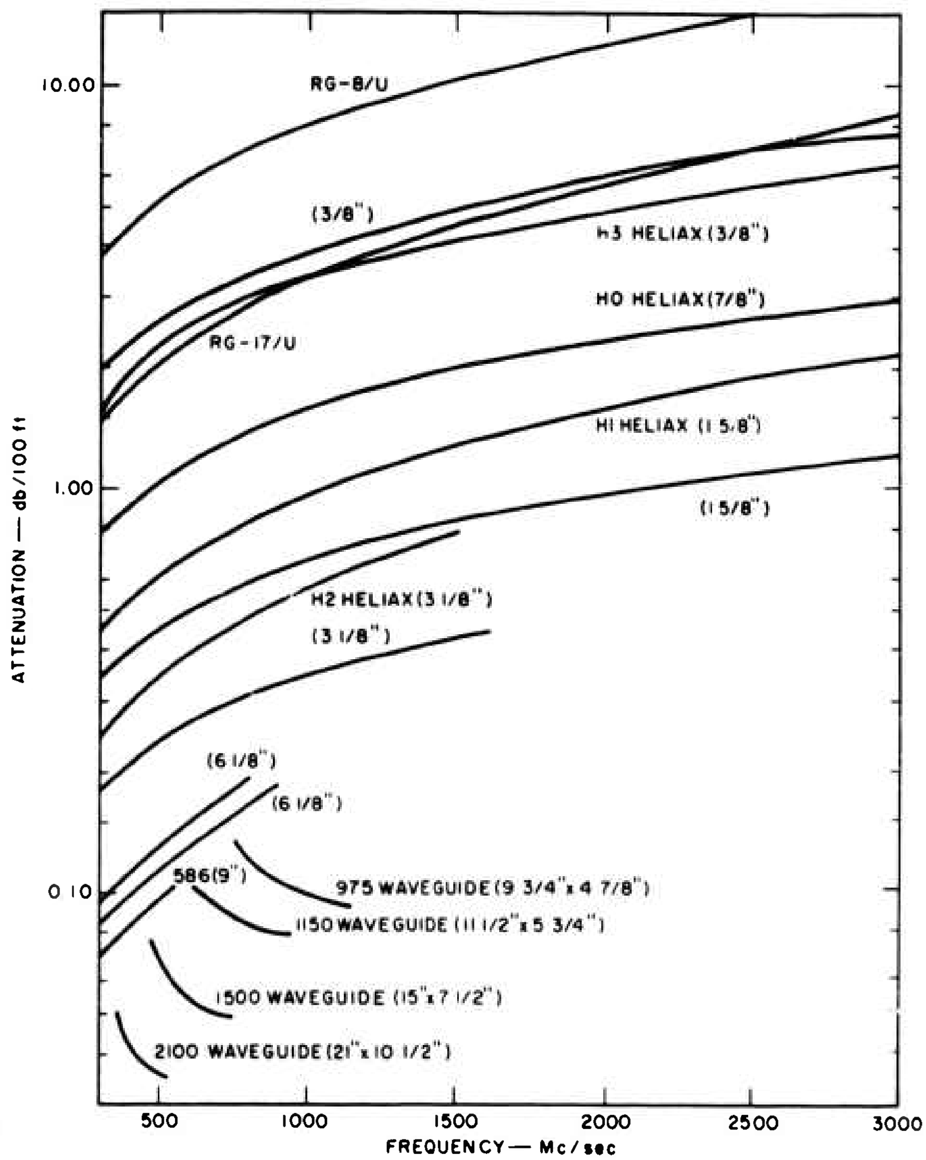


FIG. 13 TRANSMISSION-LINE ATTENUATION, 300 TO 3000 Mc

Connecting the capacitor terminals to a single spark gap has an additional advantage in that the transmission lines themselves store additional energy. Except for losses, the lines could be a multiple of a half-wavelength long for additional energy storage. Table I lists the capacitance per unit length for a few common commercial lines.

Table I

COMMON COMMERCIAL TRANSMISSION LINES

Type	Characteristic Impedance (ohms)	Capacitance ($\mu\mu f/ft$)	Nominal Voltage (kv)
RG8/U	50	29.5	10-20
RG17/U	50	29.5	20-40
RG19/U	50	29.5	30-60
RG11/U	75	20.5	10-20
20 PI*	16	124	20-40
40 PI*	16	119	40-80
100 P3*	16	136	100-130

*British Insulated Callender's Cables, Ltd. (London)

Strip transmission line is very suitable for ring transmitters, but is not readily available. Good-grade printed circuit board consisting of laminated glass or plastic material such as Teflon, with bonded copper surfaces is available in large sheets and makes excellent strip line, provided a low-loss grade of board is chosen. The characteristic impedance of strip line w inches wide and spaced t inches apart, by a material of dielectric constant ϵ (relative to air) is given by

$$Z = \frac{377}{\epsilon^{1/2}} \frac{t}{w} \quad \text{ohms} \quad .$$

The capacitance of such line is

$$C = \frac{0.225\ \epsilon w \ell}{t} \quad \mu\mu f$$

where ℓ is the length of the line and dimensions are given in centimeters.

E. Secondary Circuit Across Single Spark Gap

A second improvement in the basic spark transmitter would be to incorporate a secondary circuit across the terminals of the central spark gap. If this gap is quenched (made to extinguish rapidly) the secondary circuit will exchange energy with the ring itself in the manner of conventional coupled circuits, resulting in increased pulse length. The gap after being rapidly extinguished, ceases to be a source of energy loss. Incorporation of secondary circuitry, as suggested by Landecker, is sketched in Fig. 14. The junction of the transmission

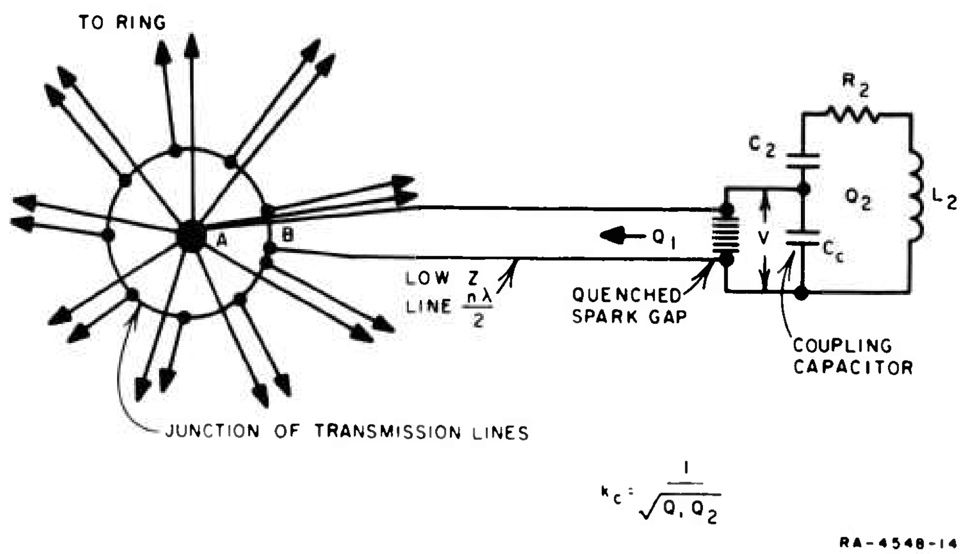


FIG. 14 CENTRAL SECONDARY CIRCUIT

lines from the ring is either connected directly to the spark gap and central secondary circuit components, or this junction is matched into a line of very low characteristic impedance, an integral number of half wavelengths long. The latter case provides additio· energy storage and allows remoting the spark gap and secondary circuitry.

There are, unfortunately, major problems associated with a central spark gap. The single transmission line from the junction of all lines coming from the ring must be of very low characteristic impedance if it is not to introduce mis-match losses. If this line is to match 50 transmission lines (each having a characteristic impedance of 50 ohms) it should have the very low characteristic impedance of one ohm. Unless the radiation resistance of the initial ring is very high, it will be difficult to realize a suitable single line joining the ring transmission lines to the spark gap.

Construction of suitable quenched gaps is not overly difficult. Quenched gaps tested in the laboratory extinguish in times as short as a microsecond, and can be made by dividing the total sparking distance into numerous small gaps of the order of 0.01 inch apart. Figure 15 is a photograph of a small quenched gap suitable for 5 to 50 kv, and capable of being filled with different gases, pressurized or evacuated. In a quenched gap no gas ion is ever very far away from an electrode surface, so that very little time is required for any ion to reach a metal surface and recombine.

The secondary circuit elements are placed across the gap as shown in Fig. 14. A serious problem arises in selecting a suitable coupling capacitor, C_c. This capacitance is typically 10,000 μμf, which at 30 Mc has a reactance of only -j 0.5 ohm. This capacitor must have a series lead inductance less than 0.001 μh if the inductive reactance is to remain comparable to the capacitive reactance. Such a capacitor is very difficult to build for high-frequency operation. A greater problem is the potential developed across the secondary circuit components C_2 and L_2. If the pulse length is to be increased significantly by the addition of a secondary circuit, the quality of the secondary circuit (Q_2) should be greater than that of the ring. Typically, Q_2 should be 200 to 300. However, with a series-resonant circuit across the spark gap, the potentials across the reactive components will rise to values of Q_2 times the voltage, V, to which the ring is charged. Thus the secondary circuit components must withstand huge voltages in comparison with the voltage on the ring. Another approach is to consider that the full stored energy of the ring must exchange with the secondary circuit, so that there will be instants of time when all of the ring energy momentarily resides in the secondary circuitry.

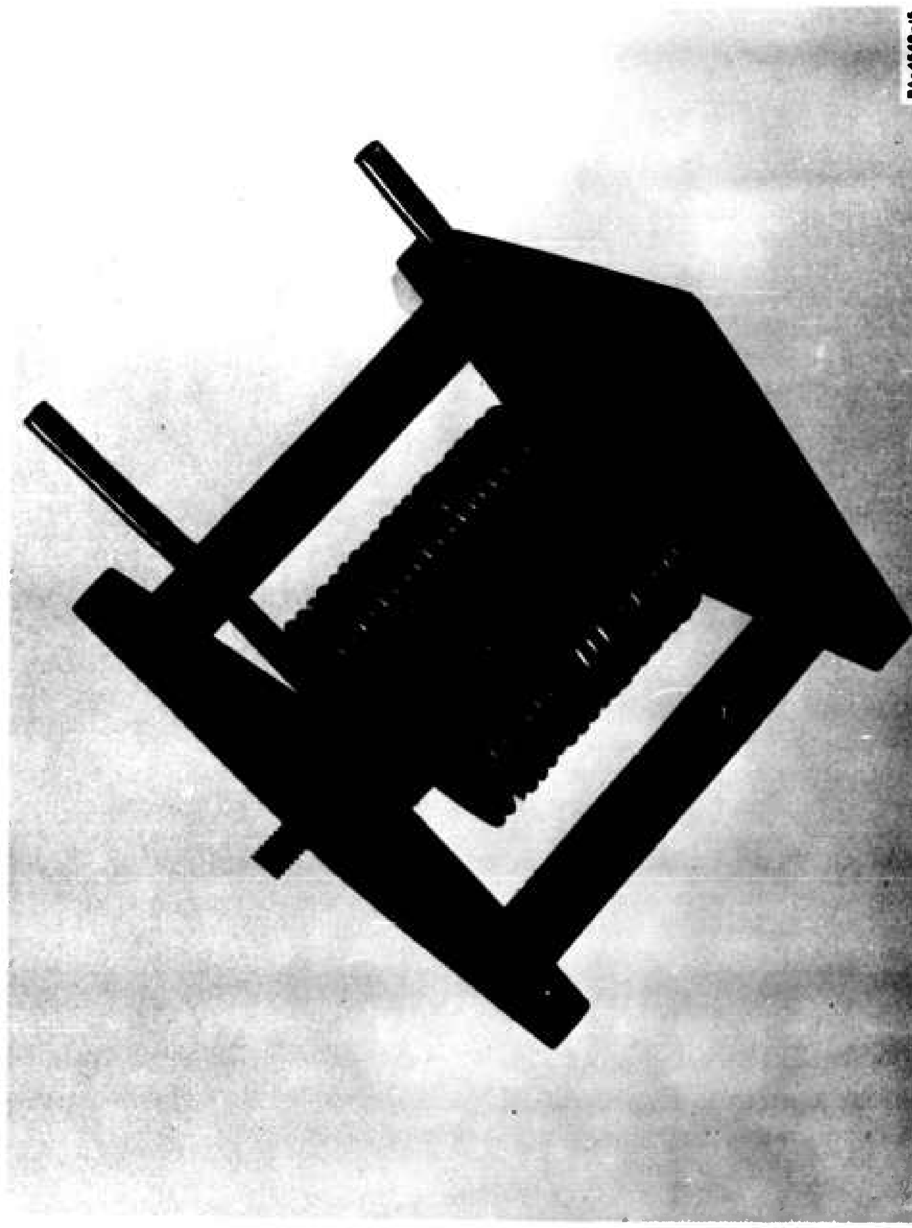


FIG. 15 QUENCHED GAP

Thus, while the single central spark gap remains a valuable improvement, provided that transmission-line losses are taken into account, the centralized secondary circuitry proves to be difficult to build in practice.

It is likely that resistance of the central spark gap can be lowered by placing a large capacitor across the gap; however, another problem then arises. The ring transmitter device is not only impulsively driven, but the possibility of other modes must be carefully controlled. A capacitor placed at the end of a length of transmission line appears at the desired frequency to be a low impedance, but at some other frequency may present a reactance which will detune the ring--causing it to oscillate at some completely different frequency, or to develop considerable energy at frequencies other than the desired single frequency. In rings built so far, this problem has been particularly severe. Transmission lines must be cut and trimmed carefully, since any small amount of reactance will shift the frequency of the entire ring a significant amount (the total capacitance of all the ring capacitors in series is only a few picofarads). Similarly, if any capacitance is placed across the central spark gap, unwanted modes of oscillation usually occur and must be carefully eliminated.

F. <u>Other Types of Secondary Circuits</u>

The difficulty of constructing a secondary circuit across the single central spark gap does not preclude using other types of secondary circuits to improve the performance of the ring spark transmitter. A suitable secondary ring can be made by constructing a second ring, nearly the same size as the first ring, but containing no spark gaps. The Q of the second ring is arranged to be somewhat higher than that of the primary ring, principally by lowering the radiation resistance of the second ring. The second ring can be located a short distance away from the first, or turned at an angle to the first ring to control the coupling, which should be adjusted close to the critical coupling, given by

$$k_c = \frac{1}{\sqrt{Q_1 Q_2}} .$$

The required mutual inductance desired may be computed from

$$M = k\sqrt{L_1 L_2} \quad ,$$

where L_1 and L_2 are the inductances of the two rings. This mutual inductance may be related to the geometry of the two rings. If the rings are concentric, but the secondary is turned at an angle, θ, with respect to the primary, the mutual inductance may be calculated from Fig. 16(a), and the relation[4].

$$M = 0.00254 D_2 \phi \mu h$$

where D_2 is the diameter of the outer ring in inches, and ϕ is found from Fig. 16(b). (D is the diameter of the inner ring.)

If the two rings are parallel and lie on the same axis D inches apart, the mutual inductance is given by[4]

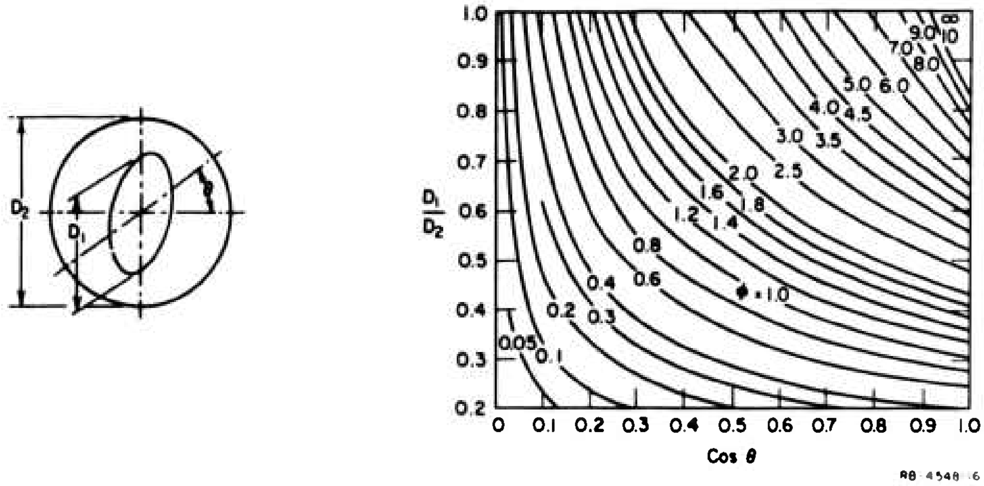
$$M = \delta\sqrt{Aa}\ \mu h \qquad A = \frac{D_1}{2} \qquad a = \frac{D_2}{2}$$

where δ is found from the curve of Fig. 16(b).

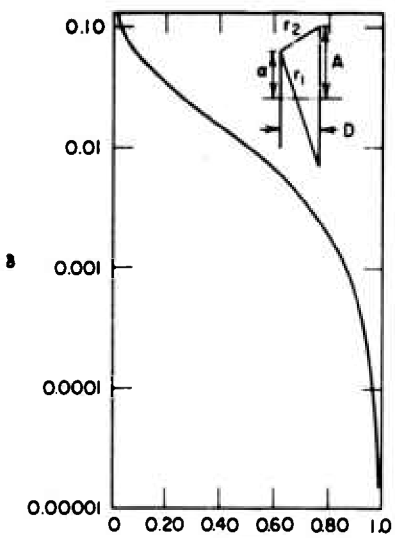
G. CW and Long Pulse Operation

Another major improvement in the ring transmitter would be the replacement of the spark gap with suitable high-speed switches that could effect CW or long-pulse operation. The spark gap operates at an impedance level of ohms, or even tenths or hundredths of an ohm. There is no great problem in turning on a spark gap switch with little pulse-to-pulse jitter, and with a turn-on time of a fraction of a microsecond. The spark gap could just as well be replaced with a thyratron or magnetron; however, any such switch has a poor recovery time, and this recovery time is the principal problem in designing a high-speed switch for operating the ring in CW or long-pulse mode.

To understand how the basic ring transmitter could be operated as a CW (or long pulse) transmitter, consider Fig. 17. L', C', R' represent the ring connected by N half-wavelength transmission lines to a common



(a)



$$\frac{r_2}{r_1} = \sqrt{\frac{\left(1-\frac{a}{A}\right)^2 + \frac{D^2}{A^2}}{\left(1+\frac{a}{A}\right)^2 + \frac{D^2}{A^2}}}$$

(b)

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FIG. 16 CURVES FOR CALCULATING THE MUTUAL INDUCTANCE BETWEEN TWO RINGS

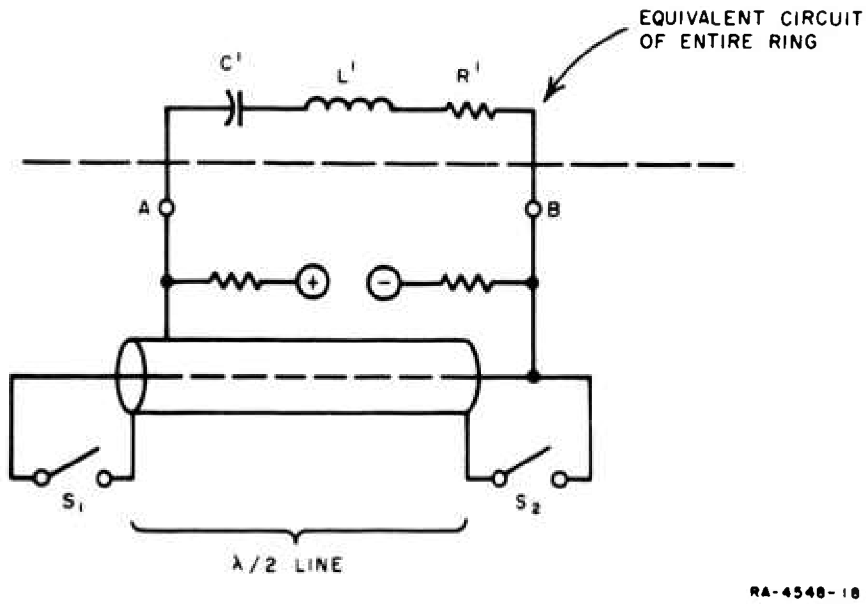

FIG. 17 CW OPERATION OF RING TRANSMITTER

junction, AB. Across this junction a low-impedance, half-wavelength line is connected, the ends of which are connected to fast switches S_1 and S_2. Such a device will produce CW output at the desired frequency, provided S_1 and S_2 are opened and closed in the proper sequence, every half RF cycle, as described by Landecker. If S_1 and S_2 are replaced by a triode, one has an ordinary vacuum tube oscillator circuit. The difficulty with ordinary transmitting tubes is that they have too low a perveance and an insufficient peak current-carrying capability for this application. The basic problem, then, is to develop a plasma device that will perform the switching function of S_1 and S_2. It is not essential that these switches be closed for a definite, controlled length of time, but it is important that they can be turned on and off in a time short compared to an RF cycle. If the plasma switch operates not as an on-off device, but as a variable resistance element, then it is necessary that one be able to effect large changes in resistance during an RF cycle.

H. Plasma Switch Devices for the Ring Transmitter

In a document describing improvements to Australian Patent #233, 302, a plasma switch was proposed for the purpose of achieving CW operation

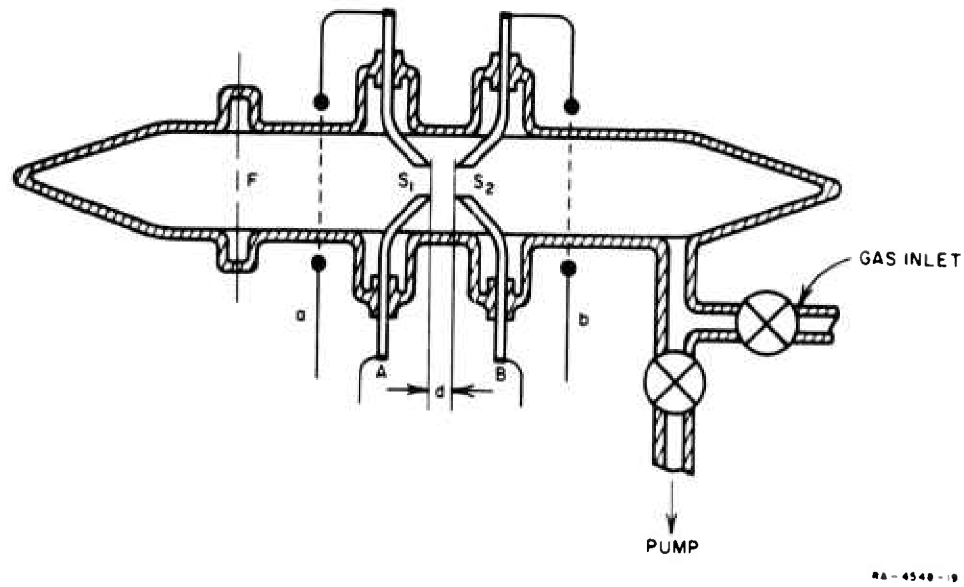

FIG. 18 ORIGINAL PLASMA-SWITCH TUBE CONFIGURATION

of a ring transmitter. A sketch of the first proposed plasma switch is shown in Fig. 18. In operation, the switch is evacuated to a pressure of 1 to 60 microns and potentials of 2 to 10 kv are impressed across the electrodes. A starting discharge occurs across the smaller electrodes marked "F" in the figure. The starting discharge produces a shock wave which, on arriving at electrodes S-1, causes a discharge across these electrodes. The new discharge in turn generates a shock wave which propagates to and causes a subsequent discharge at electrodes S-2. The process is repeated with the shock wave from the discharge at S-2 causing still another discharge at electrodes S-1. Thus the plasma switch is proposed as a nonlinear circuit element useful as a radio frequency oscillator. The crux of the proposal lies in the pressure at which the tube operates. It is necessary that at the operating pressure a discharge cannot be sustained by the electrodes except when a passing shock wave increases the charge density in the neighborhood of the electrodes. Although not clearly shown in Fig. 18, an important consideration in the design of the plasma switch is the location of the return-current leads from the upper electrodes. These leads are split, and encircle either side of the tube, thus forming backstraps for the purpose of accelerating the plasma shocks. The Lorentz force derived from the current through the backstrap accelerates the plasma shock toward the opposite electrode pair.

We have built and tested several models of the plasma switch at this laboratory. The first model constructed was almost identical with that shown in Fig. 18, and a photograph of our working model is shown in Fig. 19. A later version is shown in Fig. 20. The switch and associated circuitry were designed to operate at 1 Mc. Although many voltages, pressures, and external circuits were tested, we were unable to operate the plasma switch successfully. Typical performance is shown in Fig. 21, a photograph of an oscilloscope trace modulated by the radio output of the plasma switch. The oscilloscope trace shows a series of pulses of 1 Mc radio energy which are typical of the ringing frequency of the associated circuitry. The pulses apparently are initiated by shocks generated at the electrodes, such shocks providing additional radio energy, but at phases apparently random to the phase of previously existing energy. The pulse repetition rates appear to be governed principally by the ringing frequency of the high voltage power supply. In operating the plasma switch we experienced considerable difficulty in initiating the discharges at low pressures.

In subsequent discussions with Walter Starr at Lockheed Laboratories in Palo Alto, it was learned that multiple shocks at the power supply ringing frequency are common whenever a discharge occurs in a plasma. It was suggested that we initiate discharges in the plasma switch by using a "T-tube" placed about one meter from the plasma switch electrodes. It had been Starr's experience that subsequent shock fronts, propagating through a gas heated by previous shocks, would catch up with the first shock wave and coalesce to form a single shock front. Since this process would occur in less than a meter of propagation distance, only a single shock wave would initiate discharges at the plasma switch. The "T-tube" consists of two electrodes, in a cylindrical geometry, which form the cross of a "T." A current-return lead from one of the electrodes is placed alongside the cross of the "T," and becomes a backstrap which accelerates the shock fronts down the stem of the "T" (Fig. 22).

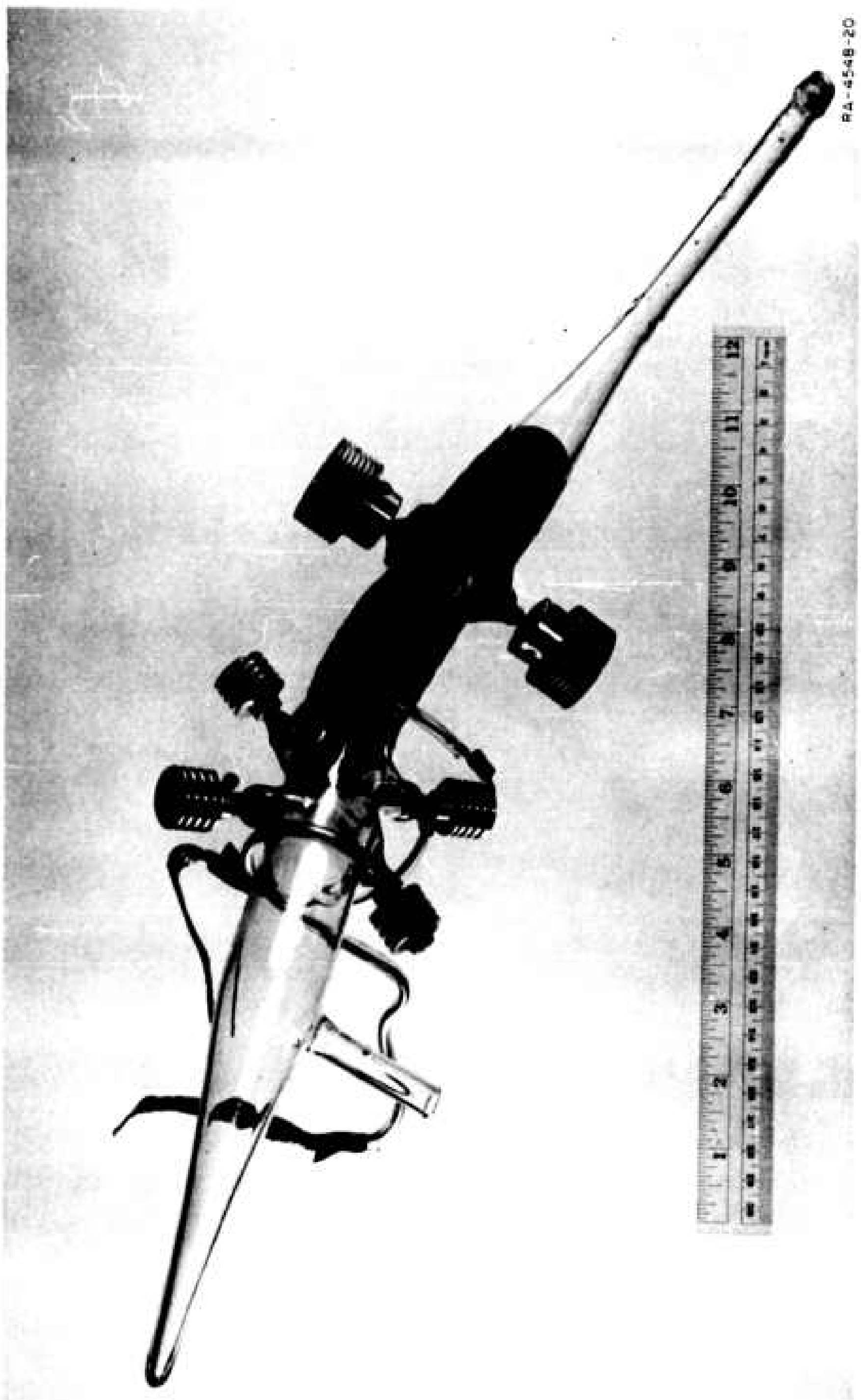

FIG. 19 FIRST EXPERIMENTAL PLASMA-SWITCH TUBE

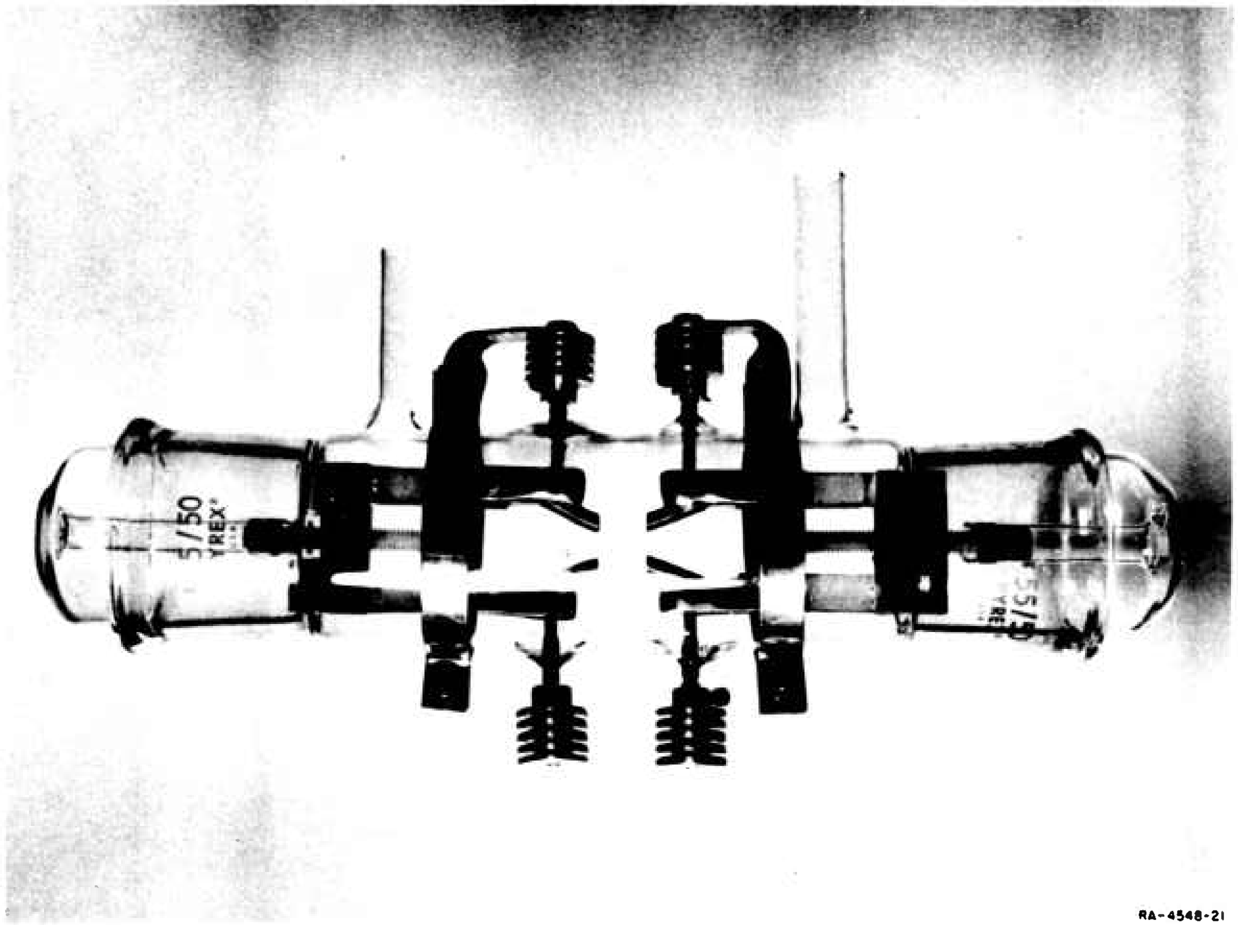

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FIG. 20 SECOND EXPERIMENTAL PLASMA-SWITCH TUBE

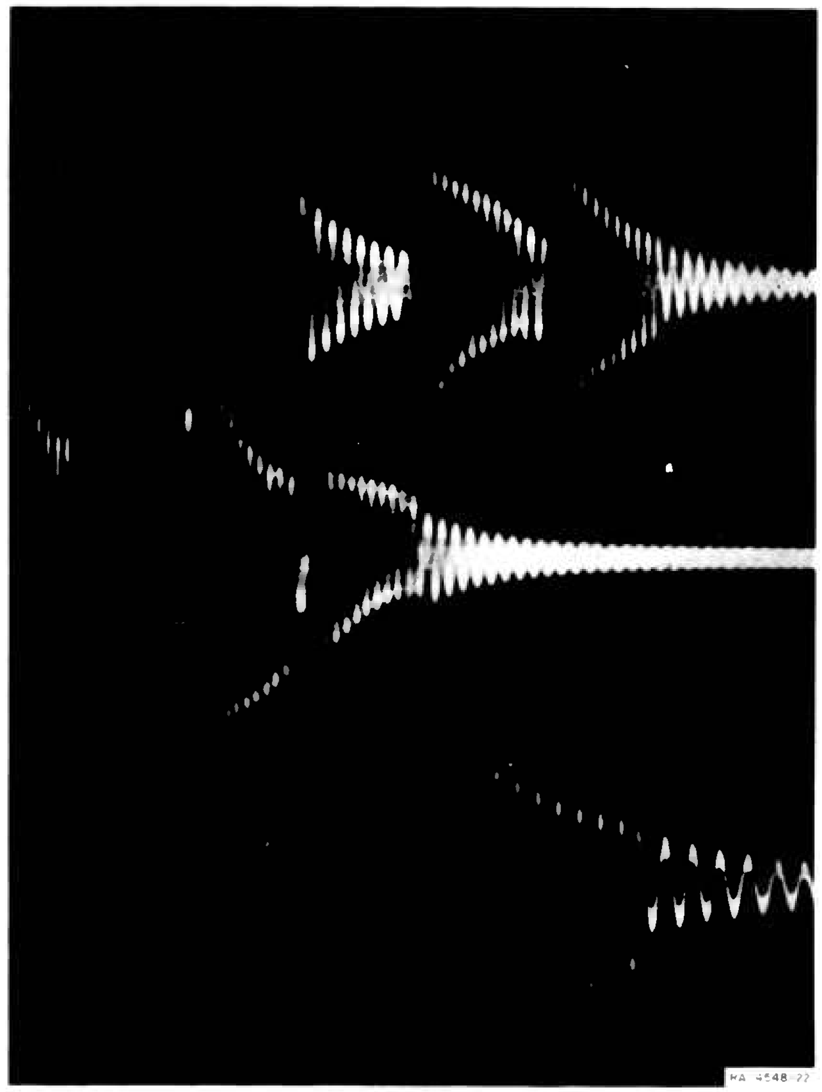

FIG. 21 WAVE FORMS OBSERVED WITH EXPERIMENTAL PLASMA SWITCH NUMBER ONE

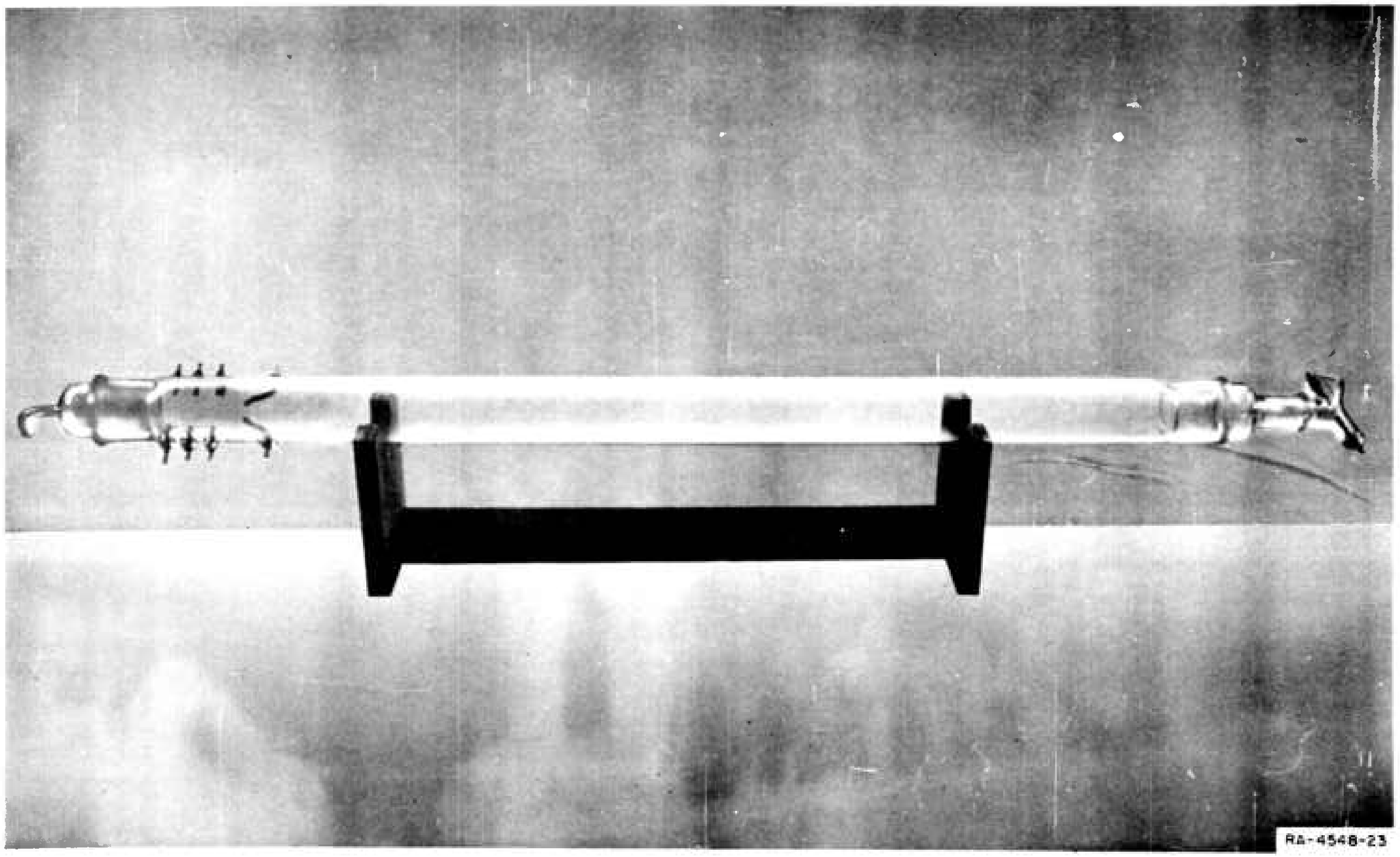

FIG. 22 ONE-METER PLASMA-SWITCH TUBE

Subsequent testing of a plasma switch with a T-tube was unsuccessful; the results achieved were essentially the same as those obtained with the first plasma switch.

A third version of a plasma switch was constructed in which the electrodes formed a cylindrical geometry (Fig. 23). In such cylindrical form the plasma switch resembles somewhat the MAST tube originated by Richard Patrick at Avco-Everett Laboratories, Boston. In Fig. 24 we show an oscilloscope photograph of the cylindrical plasma switch. The device was unsuccessful; the radio energy generated in each pulse was only the parasitic ringing of the associated circuitry.

In a subsequent discussion with Richard Patrick and Evans Pugh at Avco Laboratories, it was suggested that we attempt to use an ionization wave, rather than a shock wave, to initiate the discharges at the switch electrodes. Patrick and Pugh had found that the ionization waves travel at approximately the same speed as shock waves. Patrick felt that the small momentum of the ionization wave would allow it to be more easily controlled by the electrode geometry and external circuitry. Subsequent to our visit with Patrick and Pugh, we constructed a cylindrical switch in which the cylindrical electrodes were surrounded by magnetic coils, the coils producing a steady, longitudinal, magnetic, bias field. In operating the device we found the performance to be essentially that which we had achieved previously, and none of these devices achieved performance better than that of a quenched spark gap.

The last type of plasma switch which we constructed and tested at this laboratory was of cylindrical geometry and consisted of an outer anode split into ten separate, insulated sections (Fig. 25). An ionization wave was initiated at one end of the tube and it was hoped that the propagating ionization wave would produce a series of ten separate pulses as it passed between the ten electrodes, the ten electrodes being previously charged to a high potential. This device was also unsuccessful, and in a subsequent discussion with Kunkel at Lawrence Radiation Laboratories, we learned that the Berkeley group had observed that the ionization wave has a thickness of roughly 5 inches. The ionization wave can be thought of as a

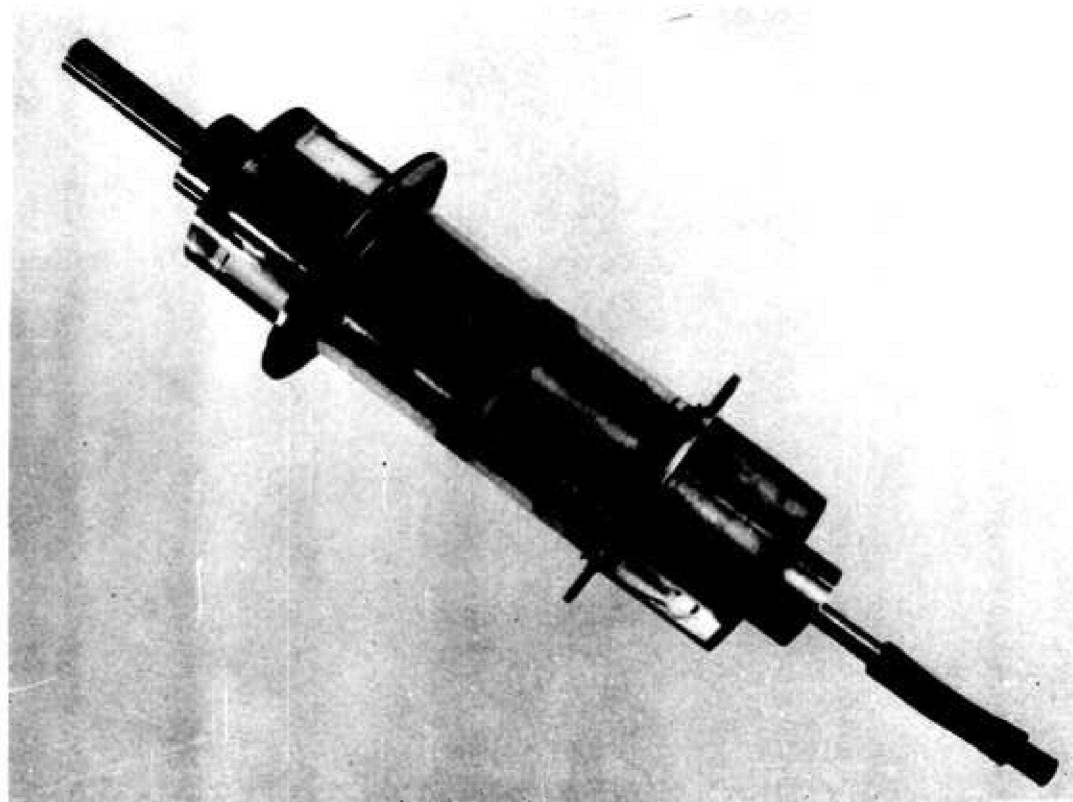

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FIG. 23 CYLINDRICAL PLASMA-SWITCH TUBE

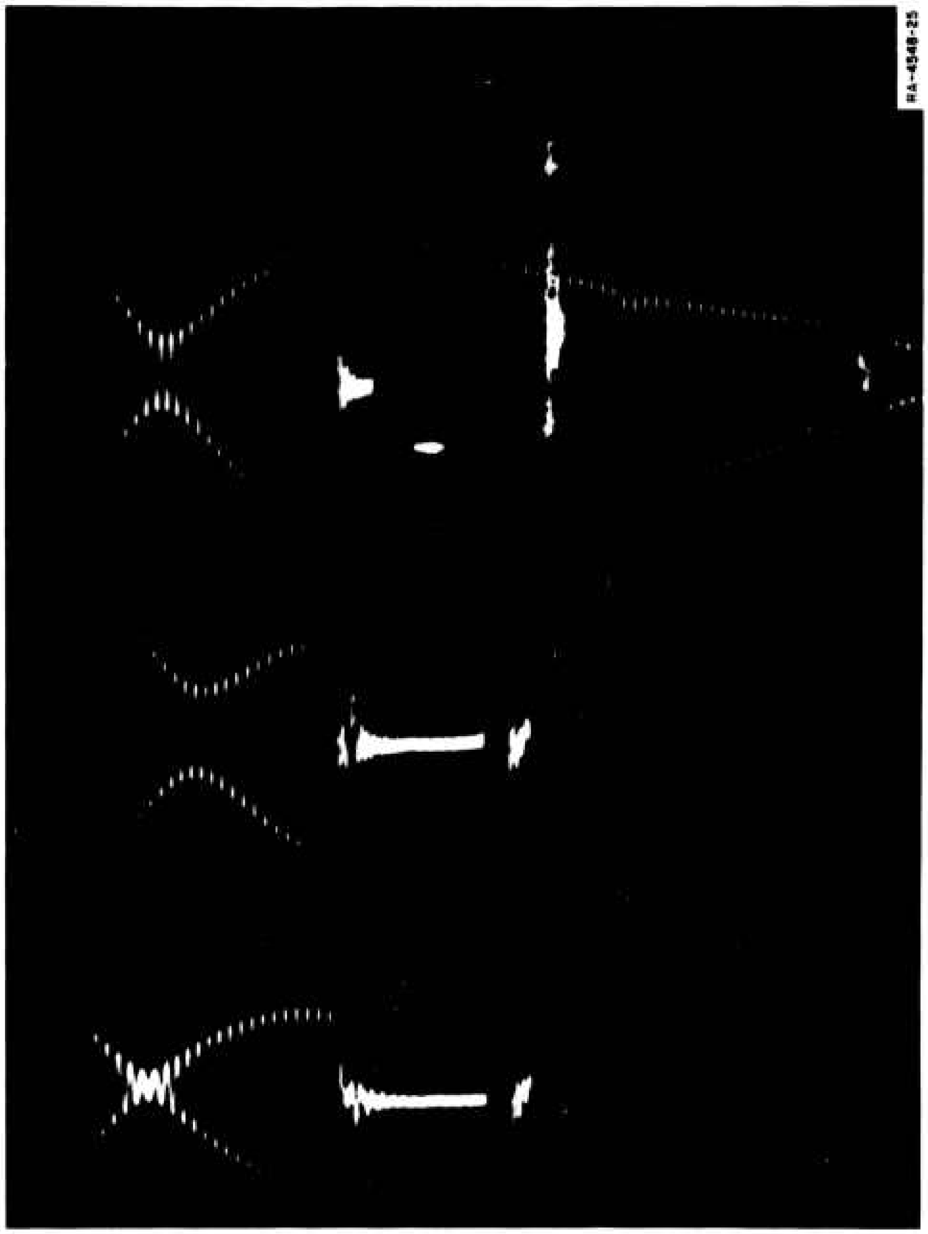

FIG. 24 WAVE FORMS WITH CYLINDRICAL PLASMA SWITCH

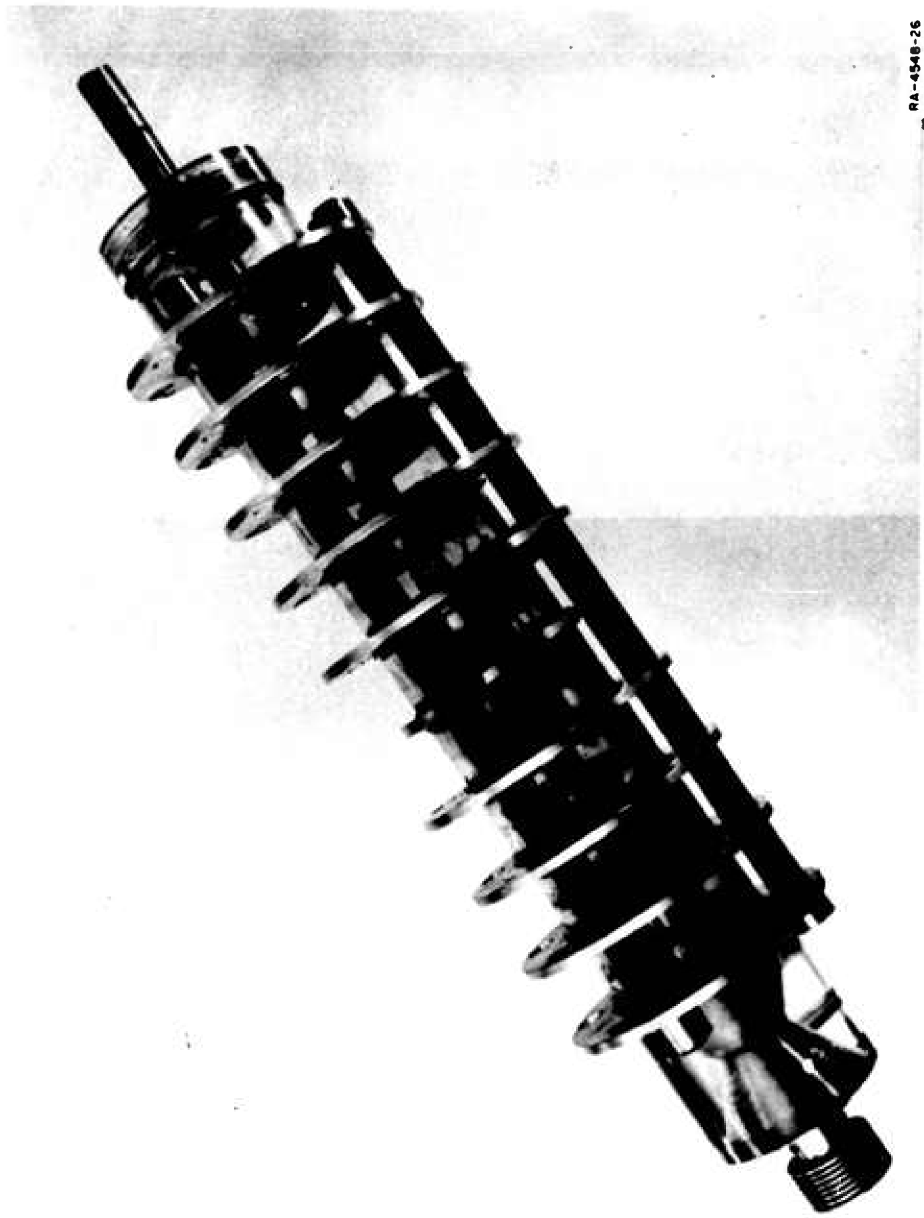

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FIG. 25 TEN-ANODE SWITCH TUBE

region of ionization about 5 inches thick, propagating in a gas which is nonconducting before and behind the ionized region. Since the speed of propagation is of the order of 1 cm/μsec, and the thickness is greater than 10 cm, we have concluded that plasma switches based on the ionization wave phenomenon will not work at the frequencies we have been investigating. Accordingly, we are no longer testing this type of device.

In our search for a means of generating high-power, high-frequency, radio energy, we have considered the possibility of using the hydromagnetic capacitor as a circuit element. In discussions with Wulf Kunkel and William Baker, inventors of the hydromagnetic capacitor, we learned that such a device would have the following limitations.

Since the dielectric constant of the hydromagnetic capacitor is

$$K = \frac{1 + 4\pi nmc^2}{B^2} ,$$

where n is the number density of the charge in the plasma, we can expect the frequency of an oscillator derived from a hydromagnetic capacitor to be variable and difficult to control. This follows from the fact that the charge density in the plasma varies during a discharge. Another limitation of the hydromagnetic capacitor as a circuit element would be the time required to get power in and out of it, such time being a measure of its upper frequency limit. Since the hydromagnetic capacitor is a coaxial device, the time required to charge and discharge it would be given approximately by the ratio of its length to the Alfvén velocity. An additional condition for operation of the device is that the angular frequency be large compared to the ion gyrofrequency. Combining these two conditions we find that to make a 30 Mc oscillator, we should have to build a rather small hydromagnetic capacitor with dimensions of the order of a few centimeters, and we should have to provide a bias magnetic field of at least 50 kilogauss. So small a device would have the inherent difficulties of high-voltage breakdown across its small insulators and excessive viscous damping owing to the friction between the rotating plasma and the walls of the container. Kunkel and Baker advised against trying to use the hydromagnetic capacitor as a high-frequency circuit element; however, William Baker, who had visited the Landecker group in Australia, suggested a storage line scheme, for generating high-power radio pulses, which will be described below.

Baker suggested storing radio energy in an open transmission line and subsequently, by means of a spark gap discharge, connecting the transmission line to a matched antenna. A schematic sketch is shown in Fig. 26. He suggested that standing waves could be excited on an

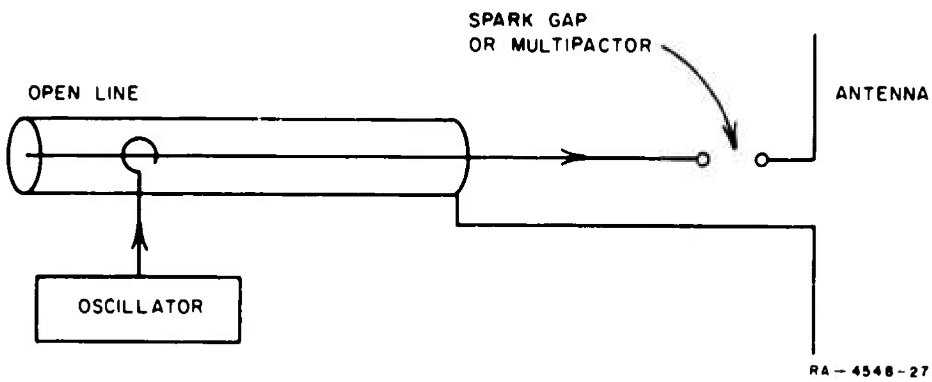


FIG. 26 CONVENTIONAL TRANSMITTER WITH TRANSMISSION-LINE ENERGY STORAGE

open transmission line by an ordinary transmitter. Subsequently, by means of a spark gap discharge, the stored energy is connected to an antenna, which has an impedance matched to that of the transmission line. The length of the radiated pulse will be given by the ratio of twice the length of the line to the velocity of electromagnetic propagation on the line. The power radiated will be Q times the input power. With a Macklich tube providing 2.5 Mw of power at 30 Mc, a Q of 1,000, and a 12-inch-diameter coaxial line 450 feet long, we might expect 2.5×10^9 watts output at 1 Mc.

We suggested the use of a multipactor in place of a spark gap discharge, and Baker agreed that this would be better. A constant bias voltage would hold the multipactor open during the time required to charge the transmission line, and removal of such bias field would connect the transmission line to the antenna.

Frank Firth, at this laboratory, has pointed out a practical difficulty in Baker's suggestion. Commercial coaxial line of 9 inches diameter is of insufficient quality to provide a Q of 1,000. Indeed, at peak power there would be a loss of 30 Mw, which exceeds the capabilities of a single conventional tube.

Myles Berg, of this laboratory, has suggested a re-entrant or circular transmission line or waveguide. The pulse length of output power could be varied by controlling the rate at which energy is coupled to the antenna; less than a perfect match would extend the pulse length beyond the length that would be determined by the physical length of the transmission line. This would be essentially a circulator in which the stored energy is impulsively connected to the antenna.

In a subsequent discussion of the above suggestions it was pointed out that an interesting possibility would be a combination of the Marx impulse generator and a re-entrant storage cavity, a possibility that will be studied in the next period.

In our discussion with Kunkel, we learned that he and Baker, in applying for a patent on the hydromagnetic capacitor, encountered interference with a similar patent application by H. Alfven. Kunkel mentioned that in Alfvén's disclosure there was included a scheme in which additional magnetic bias coils were used in a hydromagnetic capacitor to generate radio frequency power. During the next period we shall attempt to communicate with Alfvén and obtain more information about his idea.

I. Radiation Pattern and Parasitic Elements

The ring transmitter is basically a magnetic dipole radiator, and can be used in antenna arrays and structures in a manner similar to the application of the more common electric dipole antenna. The ring transmitter exhibits single-lobe radiation up to ratios of diameter to wavelength equal to 1.2. For larger rings, the pattern will be multi-lobed. The magnetic dipole antenna differs from an electric dipole in that the main radiation lobe of the magnetic dipole is in the plane of the loop. The electric vector oscillates tangentially to the ring, and the magnetic vector oscillates perpendicularly to the plane of the ring.

A great advantage of the magnetic dipole is its higher power-handling capability. The electric field at the ends of an electric dipole can rise to very high values even at modest power levels, resulting in corona and air breakdown in the vicinity of the antenna. Such breakdowns from magnetic dipoles are much more difficult to initiate, and such antennas can radiate much greater power levels than an equivalent electric dipole. Air breakdown and maximum power capability of magnetic dipole antennas are under study.

Since the ring spark transmitter radiates like a magnetic dipole, the ring can be used as an element in a linear end-fire array, as the excitation for a parabolic dish, or as an element in a broadside linear array. The use of parasitic elements is a means of controlling the beamwidth and realizing higher gains than those afforded by the ring alone. The use of additional active rings, stacked and phased, offers a possibility of increasing the peak power over that available using a single active ring with parasitic elements.

A possible application of the ring transmitter as a nonradiating oscillator should not be overlooked. By making the ratio of diameter to wavelength small, and enclosing the ring in a shielded enclosure, it should be possible to use the ring as an oscillator, coupling out only a fraction of the available power.

There are other applications where a multiple-lobe radiation pattern might be desirable, in which case a large ratio of diameter to wavelength would be used.

It is usually best to provide for a separate receiving antenna and to keep the ring array separate from the receiving system. This simplifies the TR problem and the difficulty of connecting the receiver to the transmitting array.

III CAPACITORS FOR RING TRANSMITTERS

The total inductance for a typical ring spark transmitter will be of the order of only 10 microhenries. Divided equally among 50 or 100 capacitors, the capacidance per capacitor is typically 100 to 500 picofarads. Each capacitor should be capable of withstanding very high voltages, have low dielectric losses, be physically small, and have a lead geometry amenable to the desired circular flow of current around a ring.

Capacitors to meet such requirements are best constructed in the laboratory, as few commercial types are suitable. Ordinary TV, ceramic, "doorknob" capacitors are not designed for high RF currents, but do have the right geometry, voltage range, and capacitance for many ring applications. They have been tested in the laboratory and found moderately satisfactory for high peak currents at low average powers, although their intended TV use is for bypassing and not for application to resonant circuits. Heavy-duty doorknob ceramics for transmitting applications are very good for ring transmitter applications, but have a high unit cost. Commercial vacuum capacitors are suitable, but very expensive.

Except for the possibility of having barium-titanate ceramic capacitors commercially manufactured to specifications, it is usually better to build parallel-plate capacitors in the laboratory. The capacitors used in the 300-Mc experimental ring transmitter (Fig. 27) are made in the form of concentric cylinders with polystyrene sleeves as dielectric.

All other capacitors which have been built have a parallel-plate configuration. Figure 28 shows several capacitors built in the laboratory. The small square unit uses sheet mica as a dielectric, has a capacitance of about 100 pf and will withstand 30 to 40 kv. The round unit is nominally rated at 20 kv and has a capacitance of approximately 200 pf. The dielectric is polystyrene. These capacitors will be difficult to build with uniform capacitance due to small air spaces between dielectric and

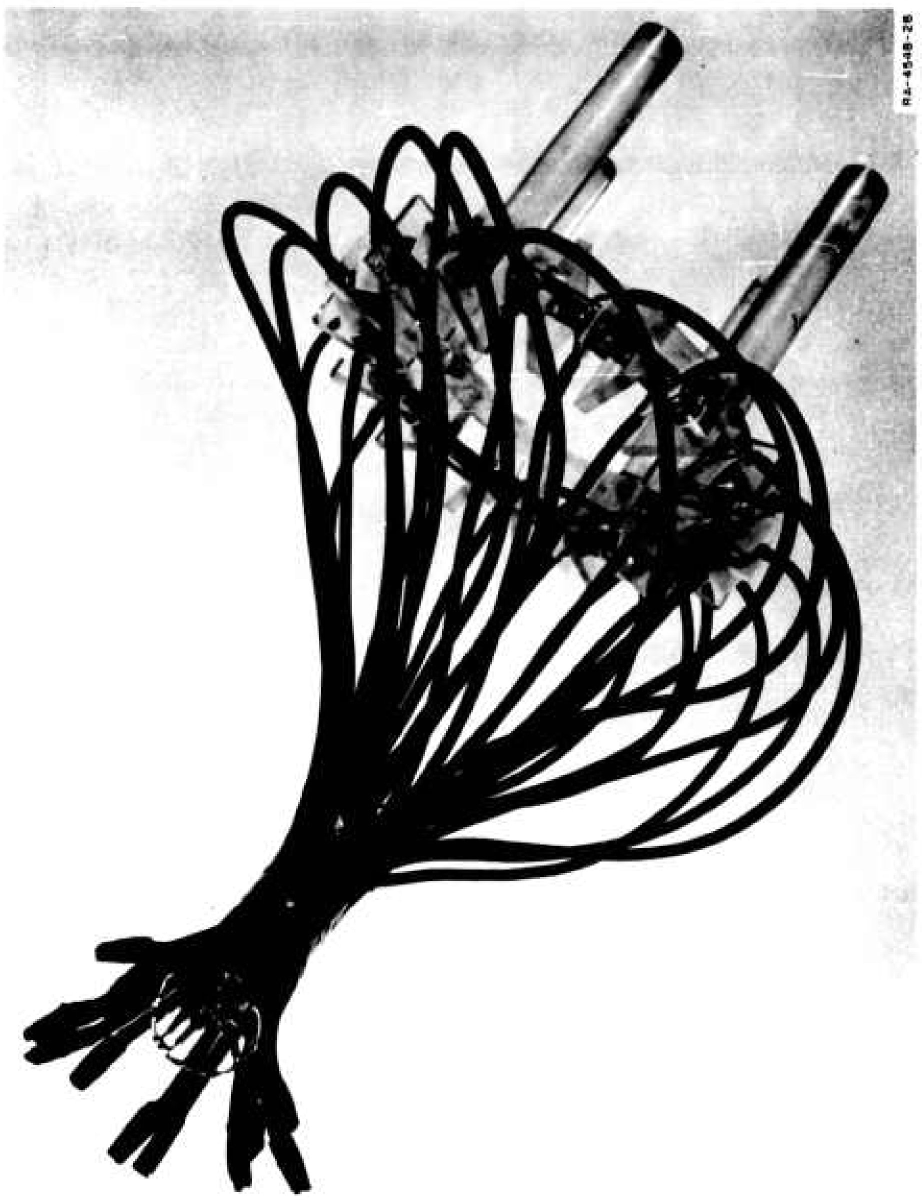


FIG. 27 300-Mc SPARK TRANSMITTER

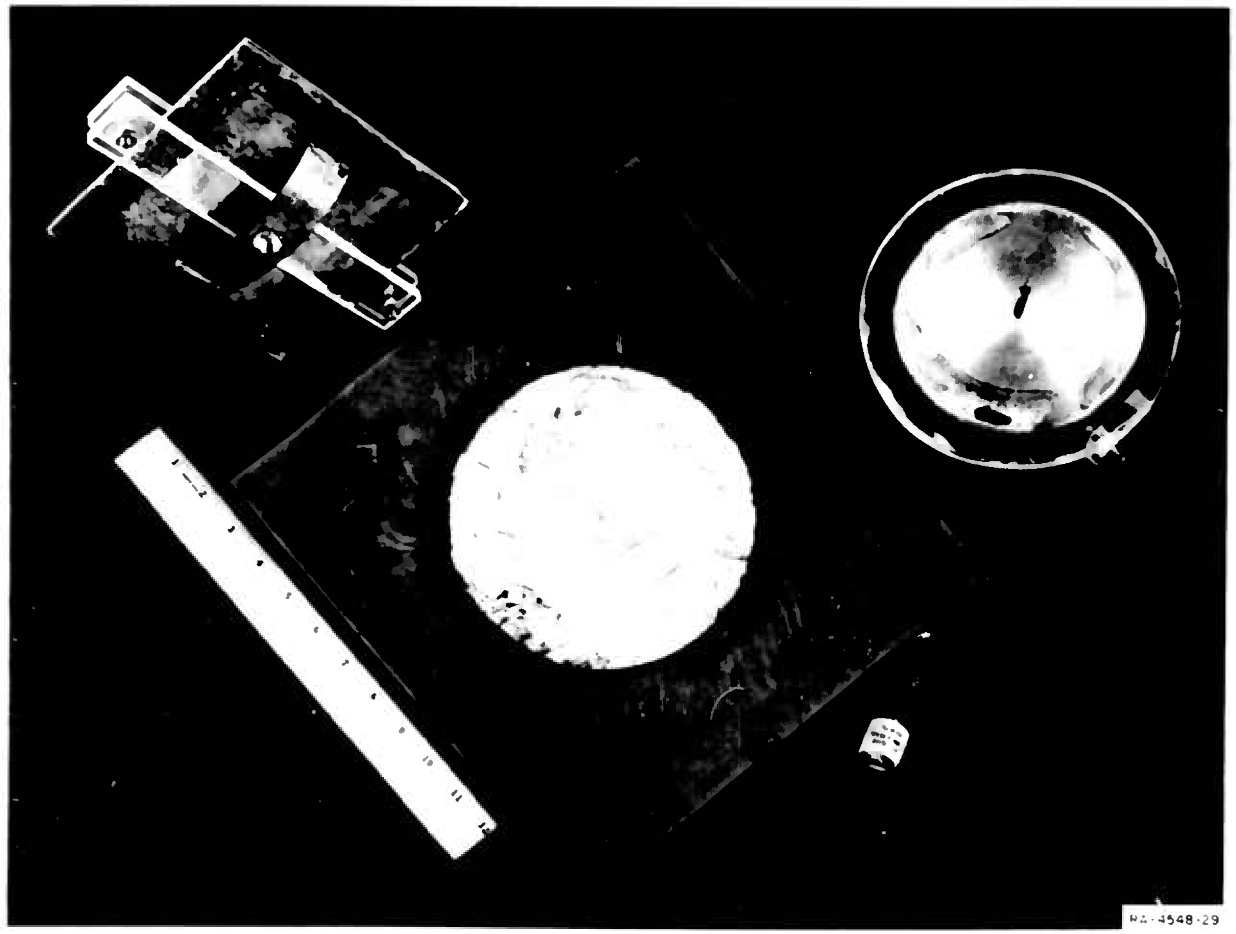


FIG. 28 EXPERIMENTAL HIGH-VOLTAGE CAPACITORS

plates. The large square unit with circular plates has been the simplest and most reliable capacitor, and was made from copper-laminated printed circuit board. This unit will withstand 120 kv and has a capacitance of 350 pf. The capacitors can be easily trimmed to within a picofarad of a common value by adding or subtracting small strips of copper from the plates.

Table II lists suitable dielectric materials and printed circuit boards for use in constructing capacitors for ring spark transmitter applications.

Table II

DIELECTRIC MATERIALS FOR RING TRANSMITTER CAPACITORS

Dielectric	Dielectric Constant	Dielectric Strength (volts/mil)	Dissipation Factor (~10 Mc)	Comments
Quartz	3.78	400 (1/4")	0.0001	Expensive, fragile
Micarta 254	4.3	1020 (0.033")	0.04	High loss
Plexiglas	2.7	990 (0.030")	0.0002	Good
Polyethylene	2.26	1200 (0.033")	0.0002	Tends to pin-hole
Polystyrene	2.56	500-700 (1/8")	<0.0001	Good
Teflon	2.1	1000-2000 (0.005-0.012")	<0.0002	Pin-holes, fails under high power
Paraffin	2.25	1060 (0.027")	<0.0002	Low melting point
Ruby Mica	5.4	3800-5600 (0.04")	0.0002	
Barium Titanate	500-2000	75-100	0.005-0.015	Low dielectric strength, non-linear dielectric
Phenolic Laminate* (copper clad)	4.3	1100 (1/16")	0.033	High loss
Paper Laminate* (copper clad)	4.0	1300 (1/16")	0.031	High loss
Epoxy (copper clad)	4.8	1000 (1/16")	0.009	Good
Teflon Glass* Cloth (copper clad)	2.5	1000 (1/16")	0.0008	Expensive

*The Budd Company, Polychem Division

IV EXPERIMENTAL RING TRANSMITTERS

The first experimental ring spark transmitter built at SRI (prior to the present contract) was designed to operate at 70 Mc. Capacitors using mica as dielectric material were constructed and assembled in a ring with individual spark gaps and no secondary circuit. Design features are summarized in Table III.

Table III

MARK I SPARK TRANSMITTER

Frequency	70 Mc
Capacitors	N = 40, C = pf
Net Capacitance	2.5 pf
Total Inductance	2.3 μh
Q	10
Radiation Resistance, R*	90 Ω
Reactance, $X_L = X_C$	900 Ω
Voltage, V	20K
Peak Power during 1st half RF cycle	80 Mw
Peak Power to 10% power level	4 Mw
Pulse Length to 10% power level	0.05 μsec

This unit was tested experimentally. The operating Q and bandwidth were verified. The pulse width was of the correct order of magnitude; however, the peak power could not be verified because of the short pulse length.

A photograph of the second ring spark transmitter built at SRI, as part of the present contract, is shown in Fig. 29. The ring was partially dismantled in the photograph for special tests that were under way. This unit, operating at 30 Mc, has been extensively tested, modified and used for several months of bread-board tests on transmission lines and secondary circuitry. The predicted design characteristics of this unit are given in Table IV.

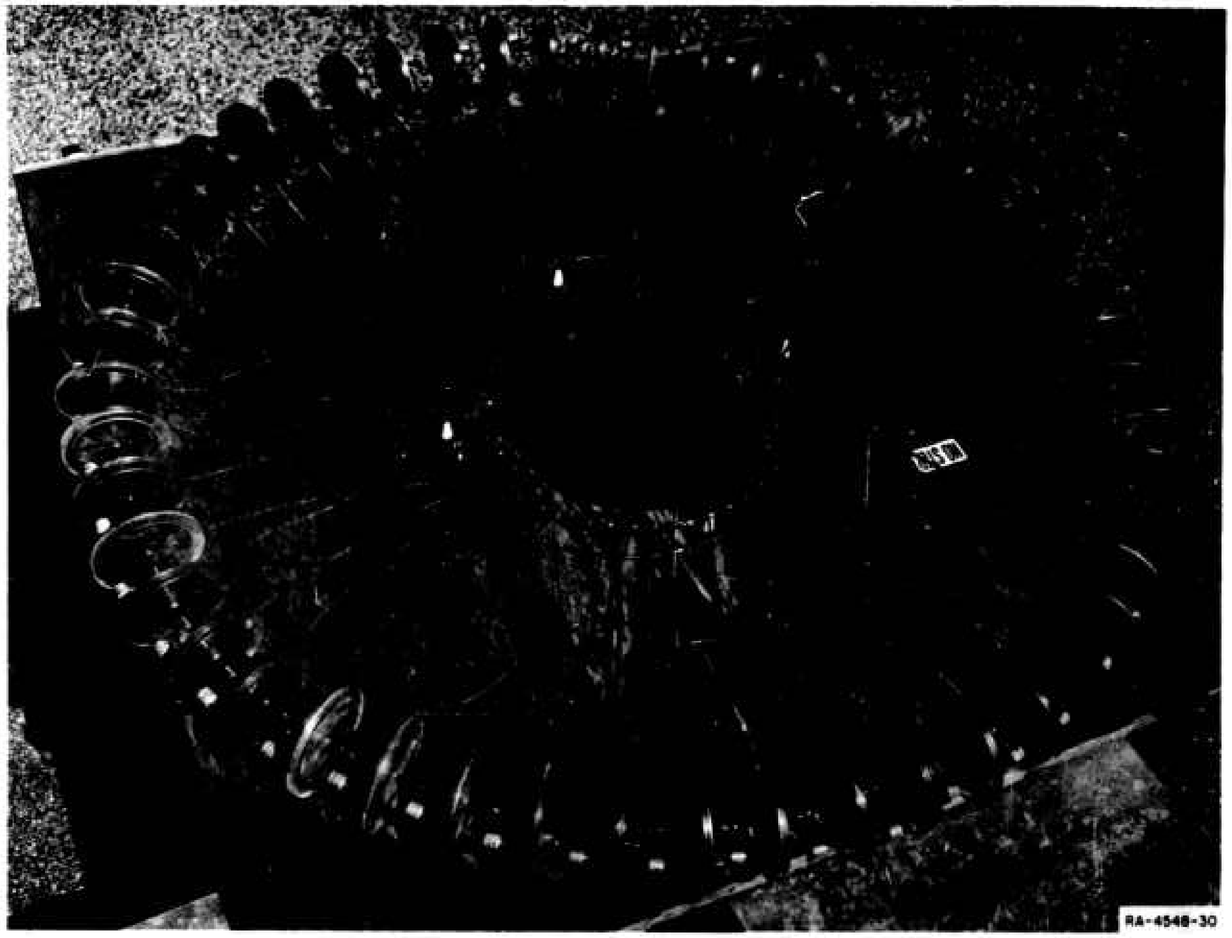


FIG. 29 EXPERIMENTAL 30-Mc TRANSMITTER

Table IV

MARK II RING SPARK TRANSMITTER

Diameter/Wavelength $\frac{2a}{\lambda}$	0.18
Frequency	30 Mc
Capacitors	N = 50, C = 220 pf
Total Inductance	6.5 μh
Operating Q	50
Radiation Resistance, R*	23Ω
Reactance $X_L = X_C$	1150
Voltage, V	20 kv
Peak Power 1st half RF cycle	10 Mw
Peak Power to 10% power level	250 kw
Pulse Length to 10% power level, without secondary	0.6 μsec
Pulse Length with secondary	6-10 μsec

The capacitors for this transmitter were fabricated using Polystyrene as dielectric. The copper electrodes were cemented to the dielectric and the whole unit surrounded with Polystyrene plates, cemented, clamped and cured in an oven to assure uniform contact of the electrodes with the dielectric and permanence of capacitance. It was found very difficult to hold the capacitance of individual units within 10 percent of the mean capacitance--which had an adverse effect on the ring performance, since each individual capacitance with its connected leads constitutes a series-resonant circuit.

This transmitter was first tested with individual spark gaps between capacitors. Measured Q was close to that predicted, and the ring was resonant at the design frequency. Peak power could not be verified because the unit was operated indoors; however, the radiated pulse was of approximately the correct length. Two half-wave transmission lines of

RG-8/U coaxial cable were next connected to each spark terminal and led to a central quenched spark gap and secondary circuit (Fig. 30). The transmission lines were arranged in balanced configurations with shields connected together and grounded at a central point to ensure balance. The ring was relocated on the roof of the laboratory so that its radiation characteristics could be studied. Measurements revealed that the secondary circuit did influence the ring performance about as expected, but that very little power was radiated at the desired frequency of 30 Mc. It was discovered that most of the energy appeared in unwanted modes and was lost as heat in the gap, or in unwanted nonradiating oscillations in the transmission lines. Further, it was found that tuning of the half-wave lines was extremely critical and adjustment of the secondary components and their location along the half-wave lines was very critical. In addition, it was not possible physically to realize a coupling capacitor with sufficiently low internal inductance to result in efficient operation in the desired mode. The fact that individual capacitors in the ring varied in capacitance by 10 percent or more also caused some concern. Despite attempts to check and verify the operation of this ring, and to make careful adjustments, the measured peak power at the desired frequency was never in excess of a few kilowatts. These results led to a careful analysis of transmission-line losses and unwanted modes, and to the discovery of the inherent problems with central secondary circuits discussed in Section I. Work on this ring was discontinued except for occasional bread-board tests.

To study ring spark transmitters at UHF a small 300-Mc ring was built (Fig. 30). This ring was operated in air as a radiator, and also in a shielded enclosure to study the effect of shielding on Q. Table V summarizes the predicted design characteristics of this ring.

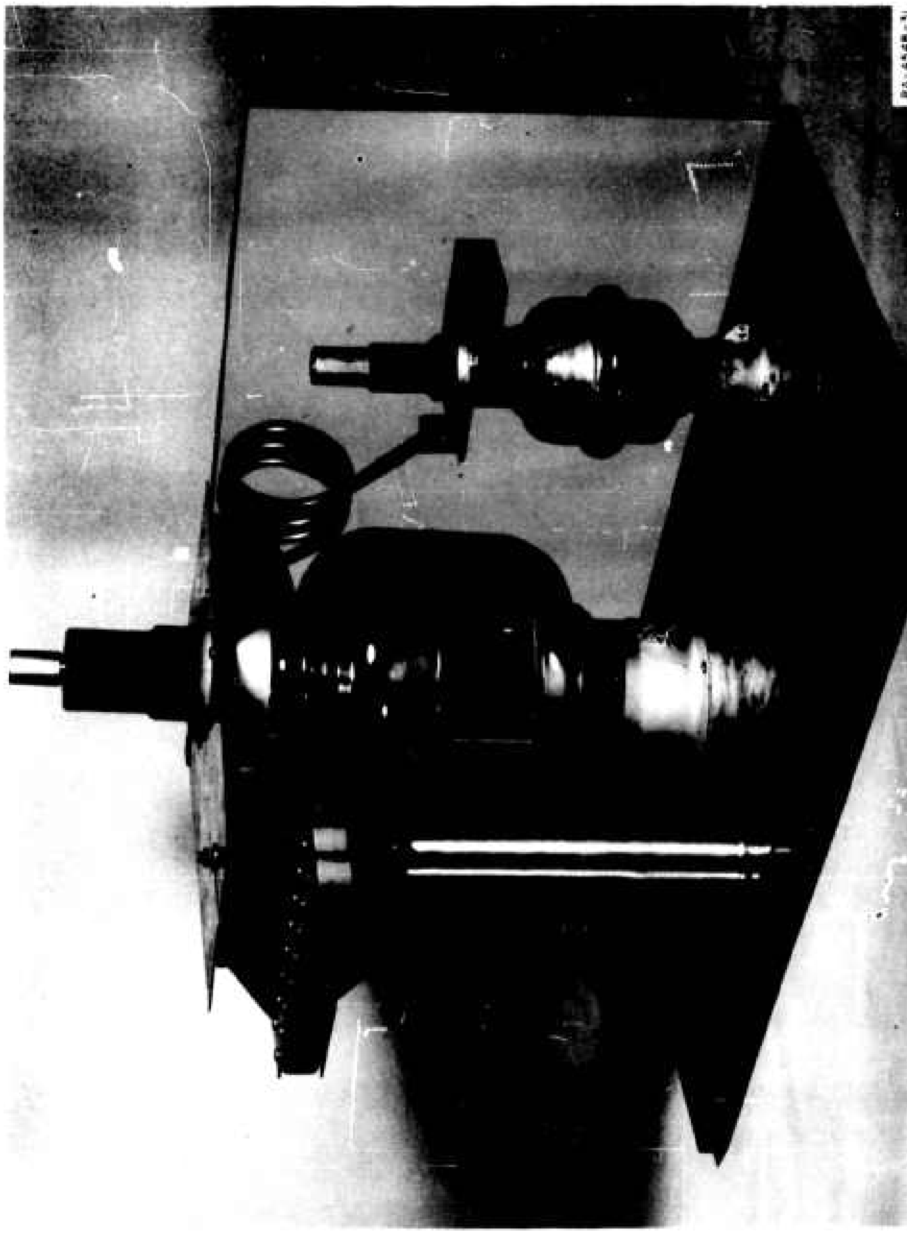


FIG. 30 SECONDARY CIRCUIT FOR 30-Mc RING

Table V

MARK III RING TRANSMITTER

Frequency	300 Mc
Capacitors	N = 16, C = 15 pf
Q	30
R*	16Ω
$X_L = X_C$	500Ω
Voltage	20 kv
Peak Power to 10%	75 kw
Pulse Length to 10% power	0.040 sec

Despite the short pulse, this unit gave several indications of operating according to theory. Difficulties were encountered when transmission lines and a single gap were employed, similar to those found with the 30 Mc unit; however because of the short wavelength, the transmission lines were only a foot long and ohmic losses were not serious. Bolometer measurements showed that more than 50 percent of the power input was converted to RF energy. We did not have instrumentation to examine the power spectrum of the device at such high frequency and short pulse length. Whether or not there are mode difficulties in this model remains to be determined. For the same reason, we were unable to determine the effect of shielding on the performance of the ring.

After the 30- and 300-Mc rings had been built and studied extensively, effort was concentrated on plasma-switch devices. Construction of a prototype high power ring with full-scale secondary circuit is now under way. This unit will incorporate ideas and modifications resulting from earlier experiments and will be used during the next few months for detailed studies on additional energy storage, pulse stretching, spark gap synchronization, secondary circuits, and peak-power measurements. Figure 31 is a photograph of a segment of the primary ring. Table VI lists the design parameters of this transmitter.

Table VI

MARK IV SPARK TRANSMITTER

Frequency	20.0 Mc
Diameter/Wavelength, $2a/\lambda$	0.19
Capacitors	$N = 67$, $C = 356 \pm 1$pf
Net Capacitance	5.27 pf
Total Inductance	12 μh
Radiation Resistance, R_1*	23.3Ω
Reactance $X_{L_1} = X_{C_1}$	1510Ω
Operating Q_1 (primary only)	65
Voltage	50-150 kv
Pulse Width to 10% power, without secondary	1 μsec
Peak Power in 1st half RF cycle	640 Mw
Peak Power to 10% point level	17 Mw
Mean Diameter	112 inches

Secondary Ring

Critical Coupling, k	0.01
Desired Mutual Inductance, M	0.09 μh
Capacitors	$N = 40$, $C = 356 \pm$ pf
Diameter/Wavelength, $2a/\lambda$	0.126
Net Capacitance	8.9 pf
Total Inductance	7.1 μh
Q_2 (secondary alone)	200
Radiation Resistance R_2*	4.66Ω
Reactance, $X_{L_2} = X_{C_2}$	920Ω
Mean Diameter	74 inches

Construction of a high power 20-Mc ring with full scale secondary is under way. This ring will be tested extensively, both with multiple gaps and with a central gap connected with low-loss transmission line, or strip line. Additional energy storage will be studied and tried. The full-scale secondary will be tested at various degrees of coupling

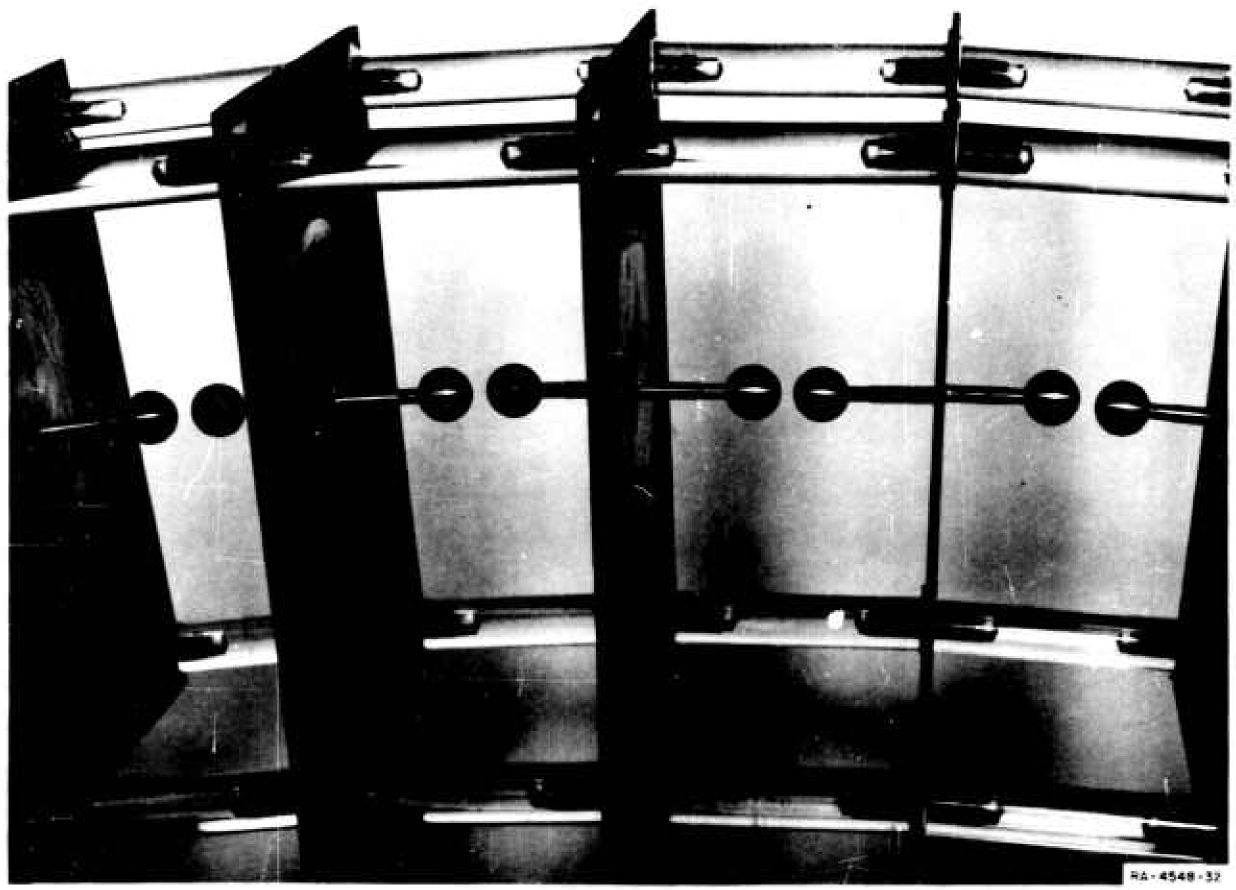


FIG. 31 SECTION OF 20-Mc TRANSMITTER PRIMARY RING

to the primary to ascertain the effect on pulse width, power output, and radiation characteristics. The radiated spectrum of these rings will be carefully analyzed.

When the full-scale ring is in operation, radiated power will be measured by several independent methods, since this quantity is difficult to measure accurately. Attempts will be made to obtain ground backscatter and meteor echoes to assure satisfactory operation.

Further visits will be made to leading plasma experts in order to explore exhaustively all possibilities for high-speed plasma switches, although it now appears that development of a plasma switch operable at frequencies of 10-100 Mc may be precluded by the inherent time limitations of plasma phenomena.

The breakdown characteristics of magnetic dipoles will be investigated in order to determine peak power-handling capability, and methods of modulation are under study. Spark losses and noise radiation will be studied quantitatively.

Frequent communication with the Australian group will be continued in order to produce timely exchange of ideas and efficient research.

V PRELIMINARY CONCLUSIONS

The ring spark transmitter is a novel and promising device for the generation of very high peak-pulse powers. It may be both simple and inexpensive. The use of suitable secondary circuits makes it possible to control the pulse shape to some extent and to obtain some control of pulse lengths. If half-wavelength lines are used to replace the multiple spark gaps of the original device with a single spark gap, and to store additional energy, one must solve the problems of the additional losses introduced by the lines and the unwanted modes.

It appears to be very difficult to connect suitable components across the central spark gap to provide a lumped secondary circuit; however, full-scale secondary rings may be a satisfactory alternative.

The principles of the transmitter are not bound to any particular frequency range. A model built at 300 Mc appears to work satisfactorily although pulse widths are very short and power output level of the first test model was disappointing. There is no lower frequency limit, except that a low frequency ring may be quite large.

The ring spark transmitter can, in principle, be adapted for longer pulse or even CW operation. However, such an improvement is contingent on the development of a suitable high-speed switch. Plasma devices were investigated because of the very low impedance levels required, and very high currents involved. The development of a high-speed switch appears at the present time to require a research effort in excess of that contemplated for this project.

Many of the problems encountered in the project to date have been of a practical, engineering nature, and further testing is necessary to prove the operation of engineering models.

Appendix

HISTORICAL REVIEW

Appendix

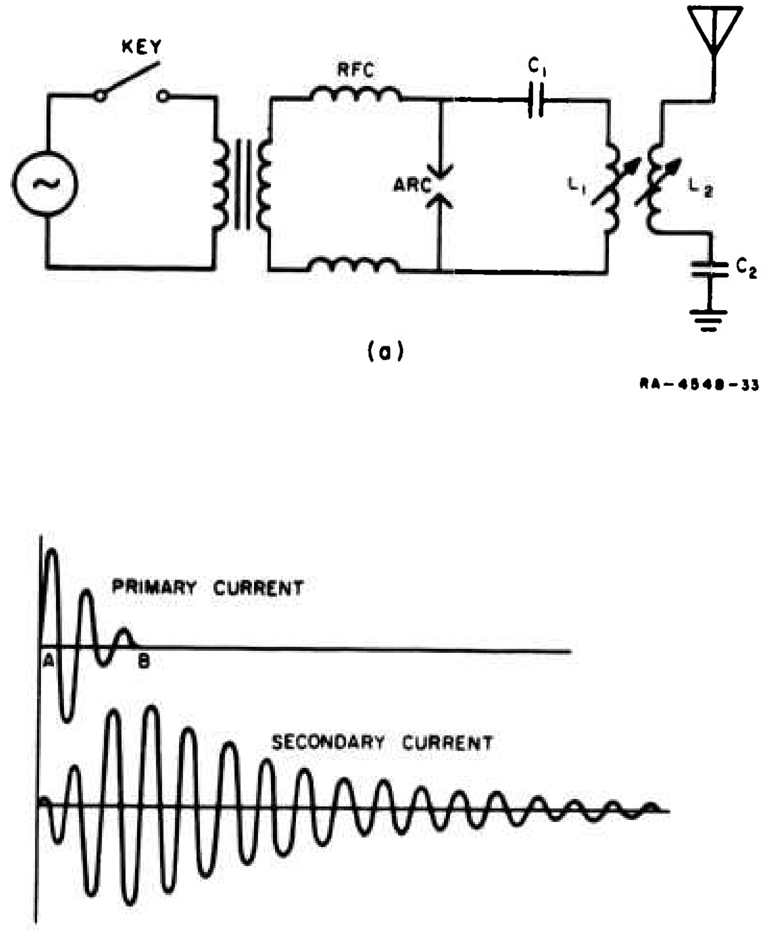
HISTORICAL REVIEW

In order to acquaint the reader with early spark transmitter devices and basic theory, the following section contains a brief discussion of early spark devices and their inherent limitations.

The first spark wireless transmitters, used in the first two decades of this century, generated damped oscillations by discharging a capacitor through an inductance. The capacitor was usually charged not with direct current but with an audio frequency tone which could be keyed by the wireless operator. The primary LC circuit was coupled to a secondary circuit and antenna so as to produce beating effects (Fig. 32). Later, the ordinary primary spark gap was replaced with various types of quenched gaps so as to interrupt the primary current at the first minimum, resulting in secondary current as sketched in Fig. 32b. Figure 33 shows resonance curves for typical spark transmitters.[2] Ordinary spark transmitters were limited to frequencies below a few megacycles.

The Poulsen arc, and similar schemes for generating CW without vacuum tubes, make use of the fact that the dynamic resistance on an arc at low frequencies is negative. The arc can be used then as a negative resistance to overcome circuit losses and produce oscillations[5] in a series resonant circuit. The volt-ampere curve for a typical arc is sketched in Fig. 34. At very low frequencies the dynamic impedance of the arc will coincide with the static characteristic, A. At higher frequencies, the application of a sine wave across the arc will result in volt-ampere curves such as B and C. As the frequency is increased this ellipse will flatten and eventually be that of a pure resistance (D). The cause of this behavior is the finite ionization and de-ionization times in the plasma of the arc.

When an intense magnetic field is used to quench the arc rapidly and sweep out ionization from the gap, it is possible to maintain a negative dynamic resistance to frequencies of the order of 0.5 Mc. This is the basis of the Poulsen arc transmitter[6] which was used extensively thirty years ago. (See Fig. 35.)



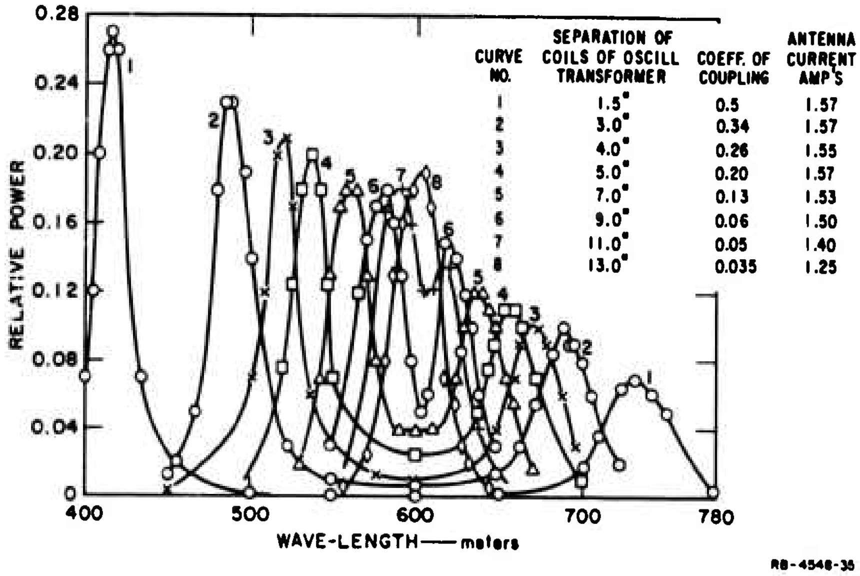
(a)

RA-4548-33

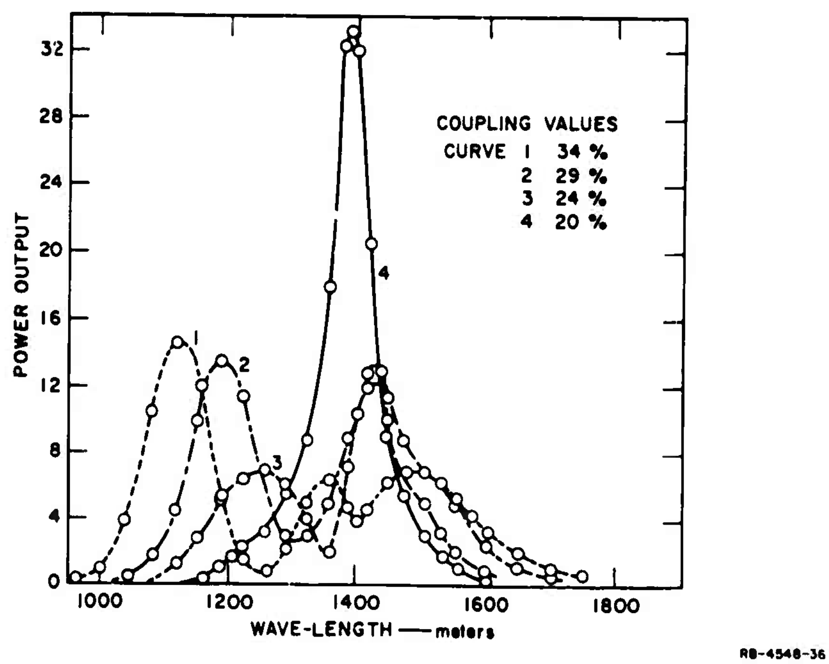
(b)

RA-4548-34

FIG. 32 EARLY SPARK TRANSMITTER AND WAVE FORMS



(a) NONQUENCHED PRIMARY GAP, RESONANCE CURVES FOR A 60~, 3 KW., OPEN SPARK TRANSMITTER PRIMARY & SECONDARY OF OSCILLATION TRANSFORMER TUNED TO 600 METERS, PRIM. CAPACITY = 0.0051 μf, SEC. CAPACITY = 0.0017 μf, ANTENNA RES. = 4 ohms.



(b) QUENCHING GAP

FIG. 33 TYPICAL SPARK TRANSMITTER RESONANCE CURVES

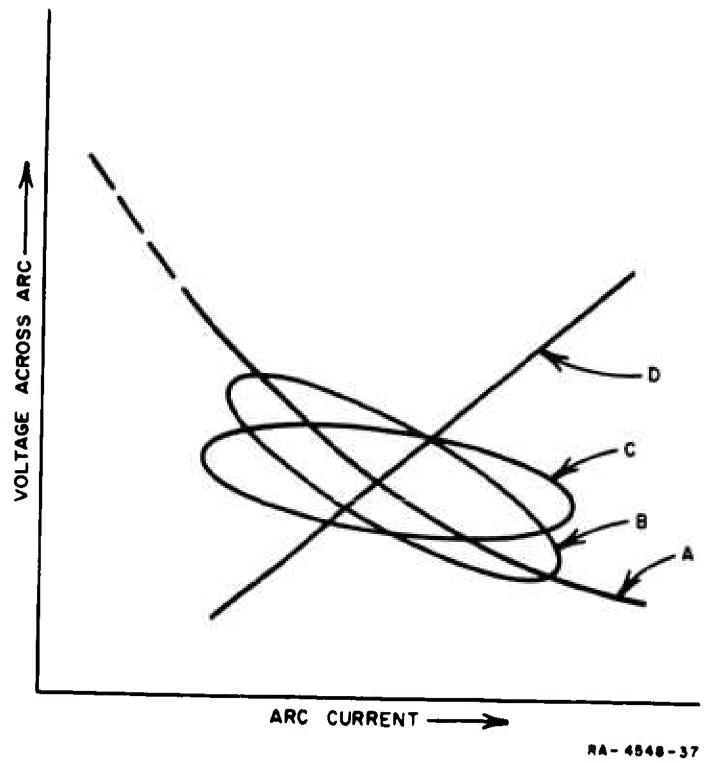


FIG. 34 DYNAMIC CHARACTERISTICS OF A DC ARC

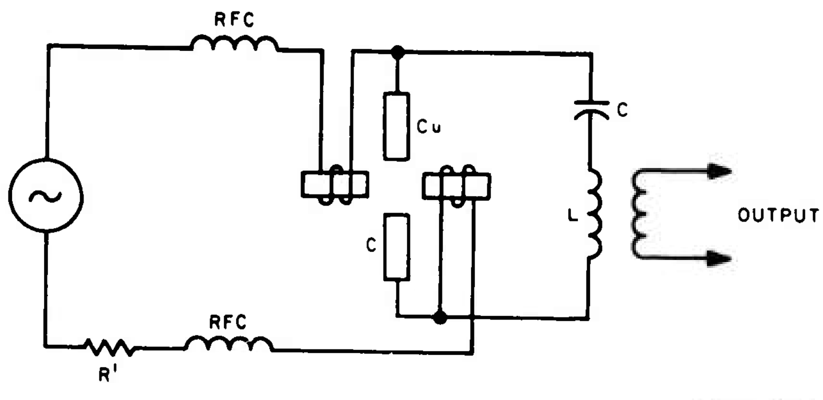


FIG. 35 POULSEN ARC TRANSMITTER

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